Self-Interacting Dark Matter from a Non-Abelian Hidden Sector

Tim M.P. Tait

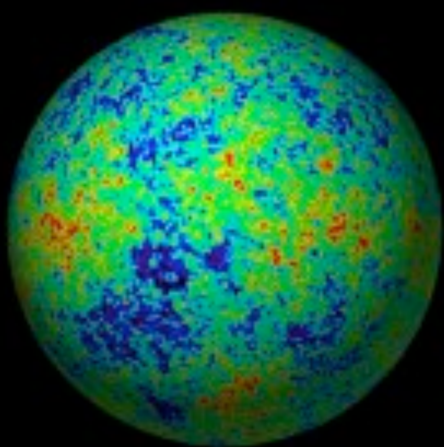
University of California, Irvine

K. Boddy, J. Feng, M. Kaplinghat, TMPT
1402.3629 [hep-ph] & PRD
+ Y. Shadmi 1408.6532 [hep-ph] & PRD

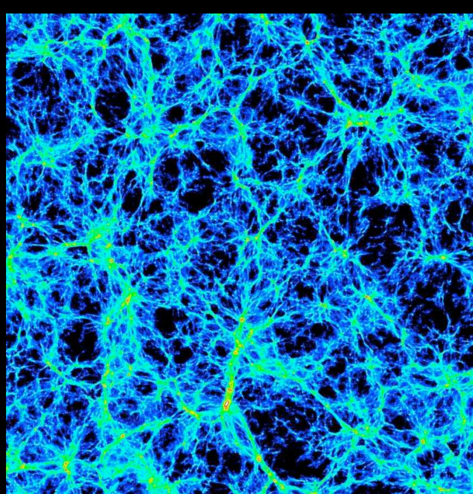
Lattice for BSM
April 22 2015

Dark Matter

CMB

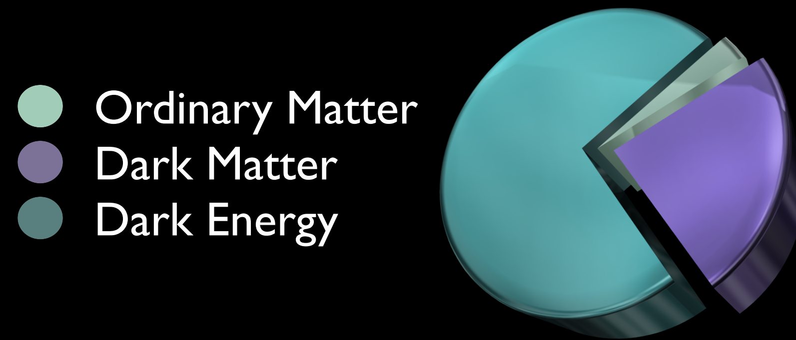


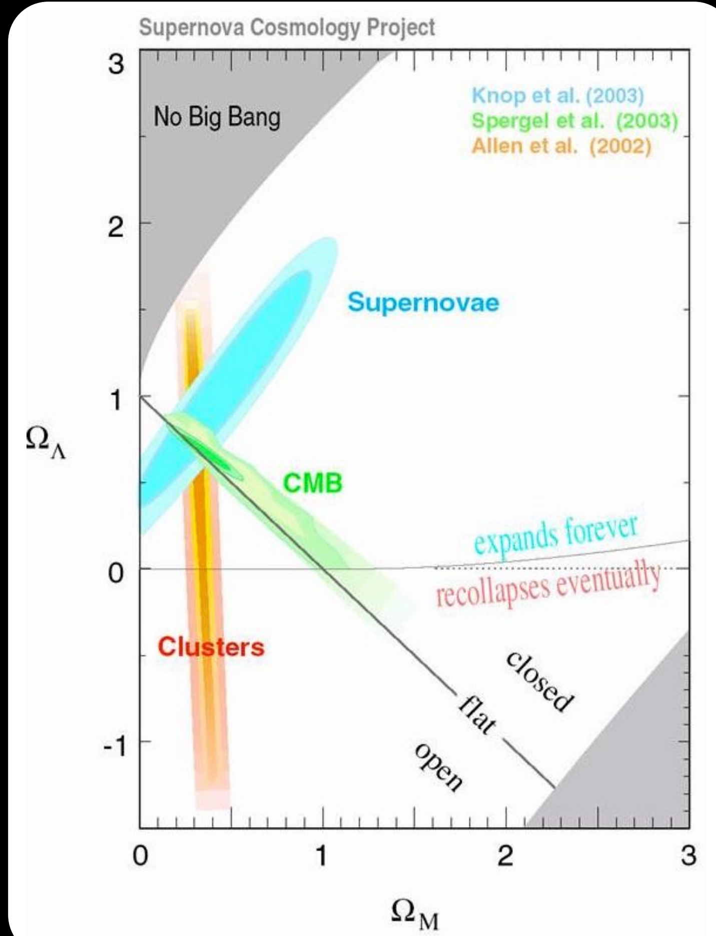
Supernova

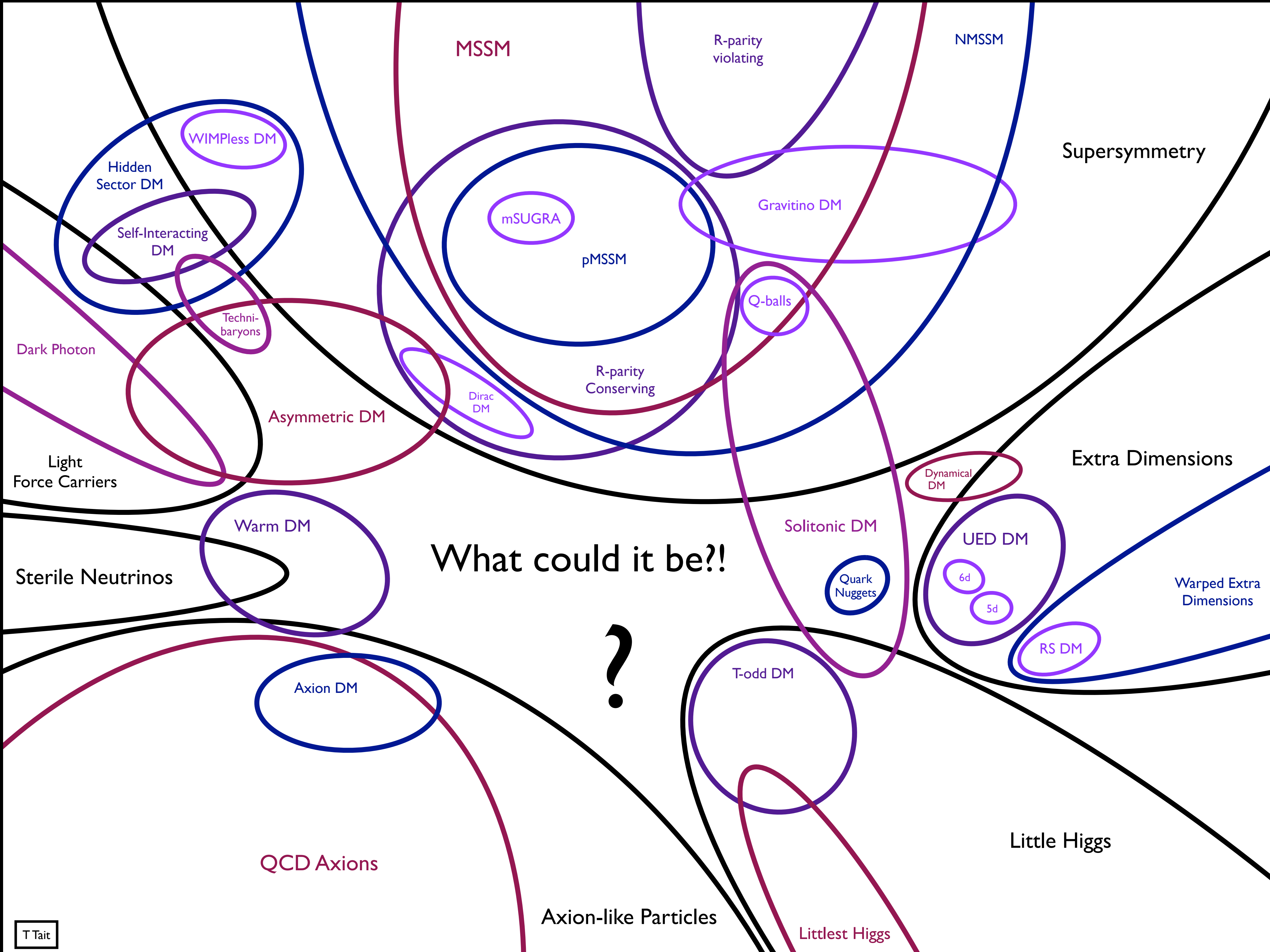


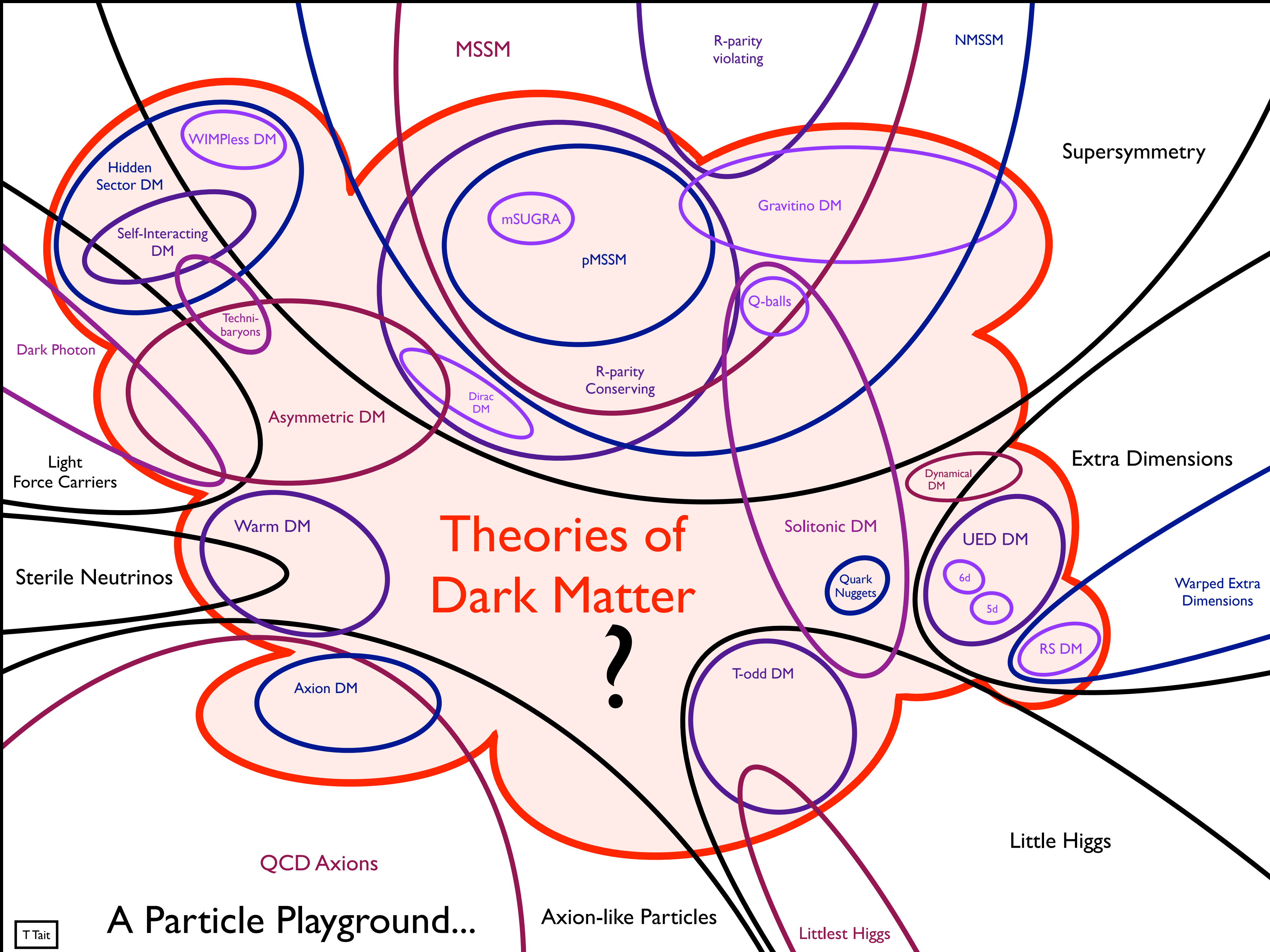
Structure

Lensing






MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Gravitino DM
mSUGRA
pMSSM
Q-balls
Techni-baryons
Dark Photon
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Solitonic DM
UED DM
What could it be?!
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
?
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait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Theories of Dark Matter
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A Particle Playground...
Axion-like Particles
Littlest Higgs
T Tait

Dark Matter

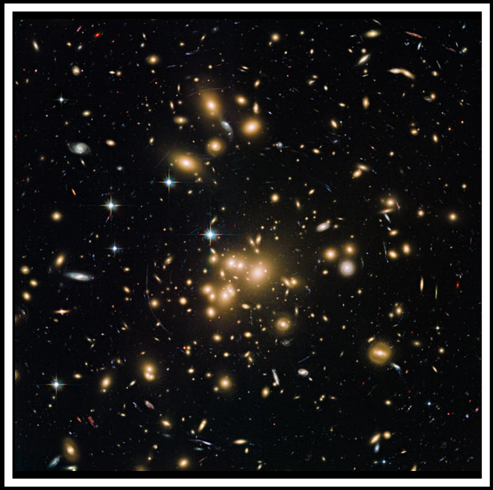
“Cold Dark Matter: An Exploded View” by Cornelia Parker

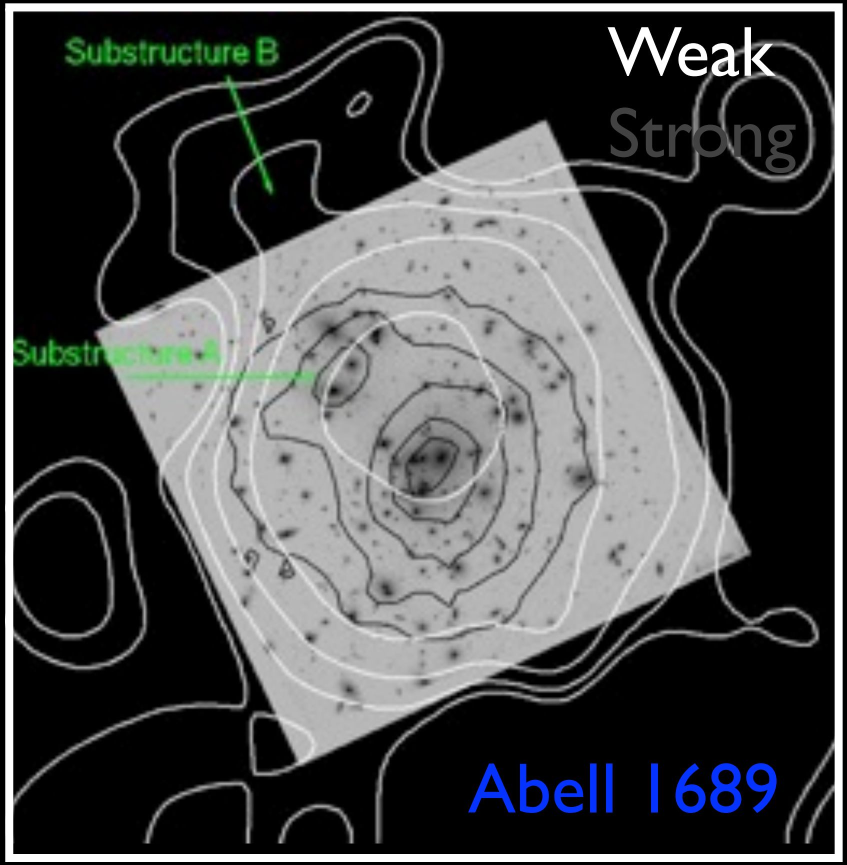
- The standard picture holds together remarkably; many different observations at many different length scales are all described by a Universe containing dark matter.
- For me, this is a large part of the reason why dark matter seems much more likely to explain the data compared to alternatives such as modified gravity.
- Nonetheless, we will see that there is some tension with observations of the smallest scales of structure.

Small Scale Structure

Galaxy Clusters

- Clusters of galaxies provided some of the very first evidence that dark matter was needed, and they remain interesting laboratories to study it today.
- We can study the dark mater content of galaxy clusters using a variety of tools.
  - The innermost regions can be probed by the motion of stars in the central galaxy.
  - Strong gravitational lensing probes the intermediate scales of the cluster.
  - Weak gravitational lensing tells us about the outer parts of the cluster.





Galaxy Clusters

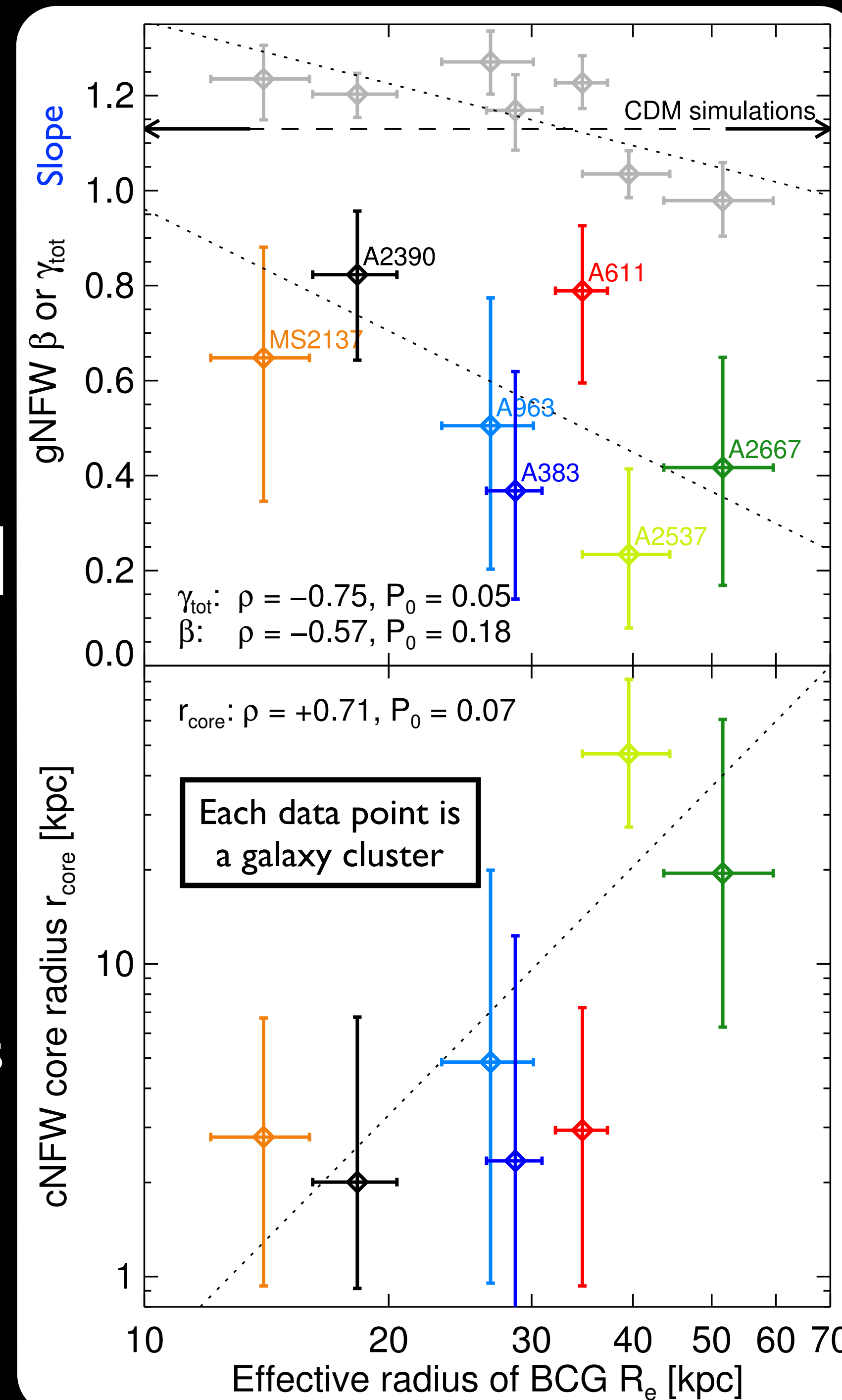
- N-body simulations of collision-less dark matter (CDM) predict a peaked distribution following a generalized NFW distribution:

$$\rho(r) \propto \frac{1}{r^{\beta}(r_s + r)^{3-\beta}}$$

with β typically around 1.

Newman et al (2012)

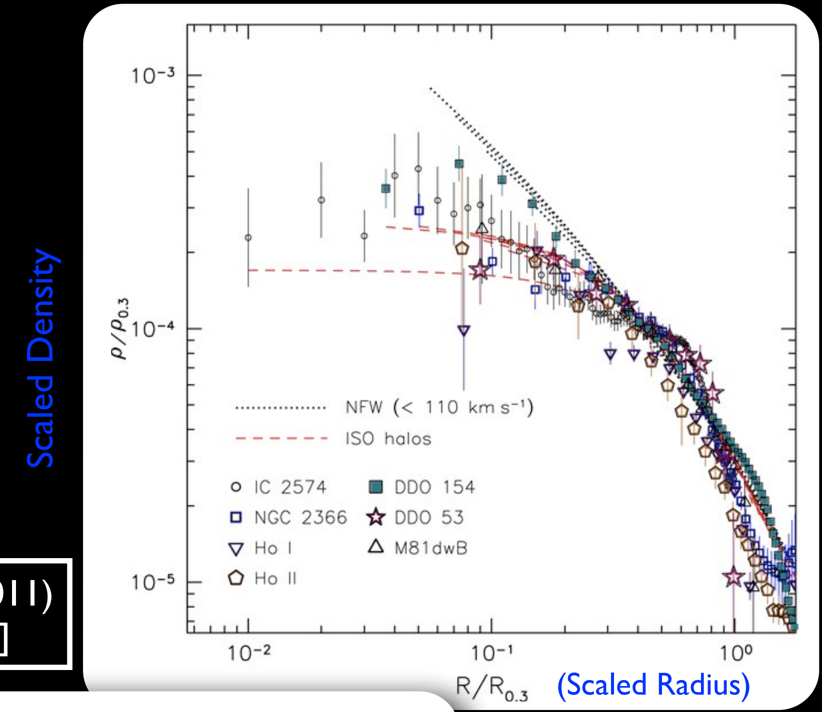
- Putting together characterizations of the density at different radii, one can measure the slope parameter for various galaxy clusters with masses around $10^{15} \times M_{sun}$.
- The measurements cluster at smaller slope parameters, indicating profiles which are less peaked than expected from simulations.
- If one fits a cored profile instead, the fit indicates cores on the order of 1 to 10 kpc.

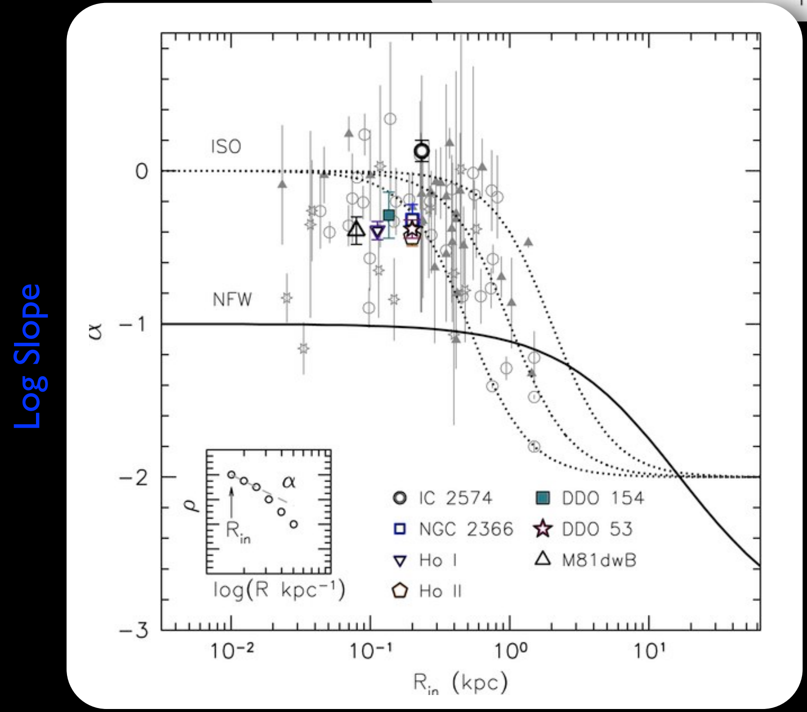


Dwarf Spiral Galaxies

- We can also see something strange going on with dwarf spiral galaxies.
- For some galaxies, one can reconstruct the rotation curve as a function of the distance from the center, and study the shape of the dark matter distribution.
- The data shows some preference for cored profiles, even in these dwarf spiral galaxies.

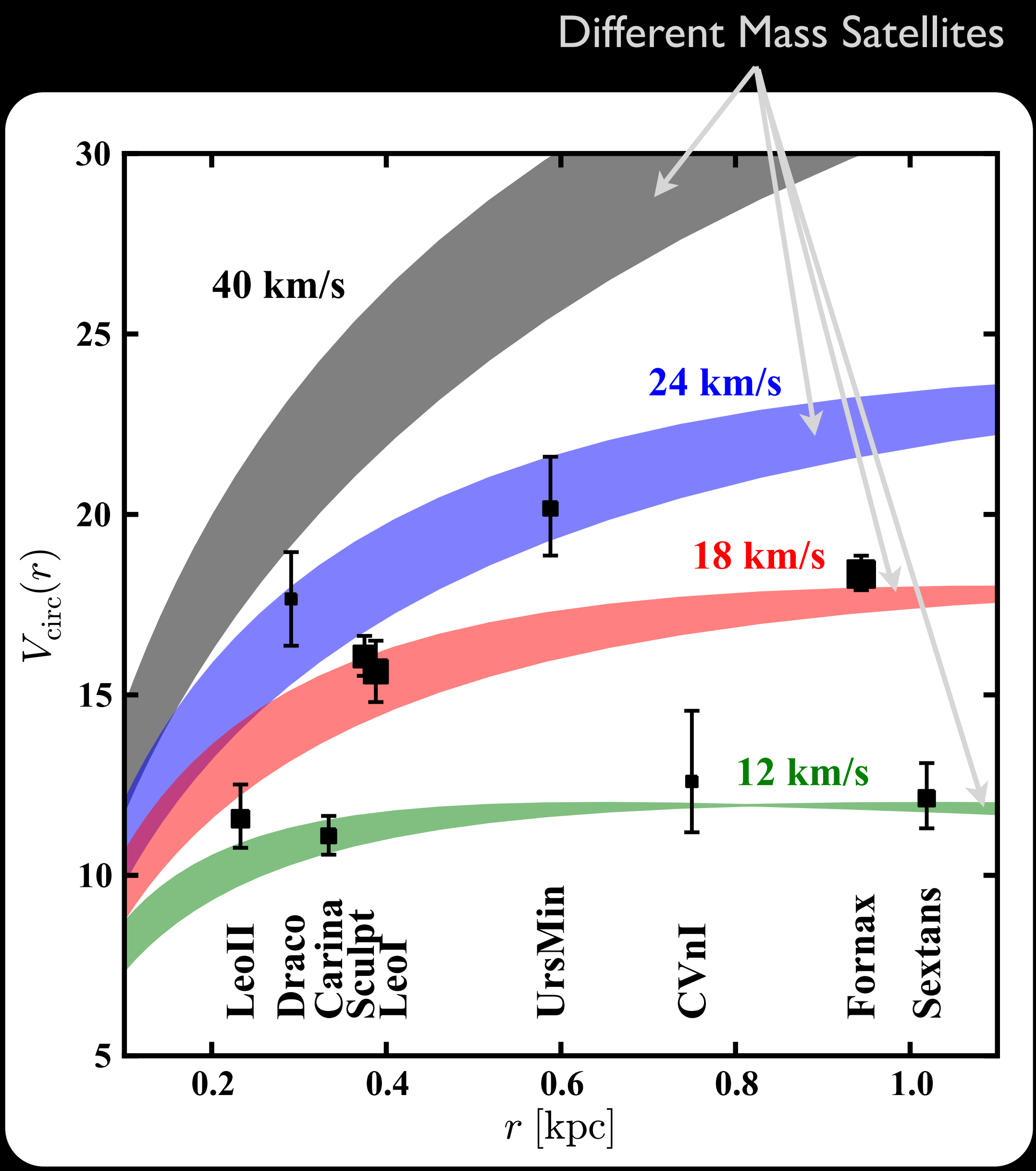
Oh et al (2011)
[THINGS]





Dwarf Spheroidals

- We can also do population studies on the dwarf spheroidal galaxies of the Milky Way.
- These systems are dominated by their dark matter content.
- In this case, the dark matter densities can be inferred by the velocity dispersion of the stars they contain.
- Comparing with simulation, we can ask whether we see the expected distribution of satellite galaxies for a galaxy like the Milky Way.

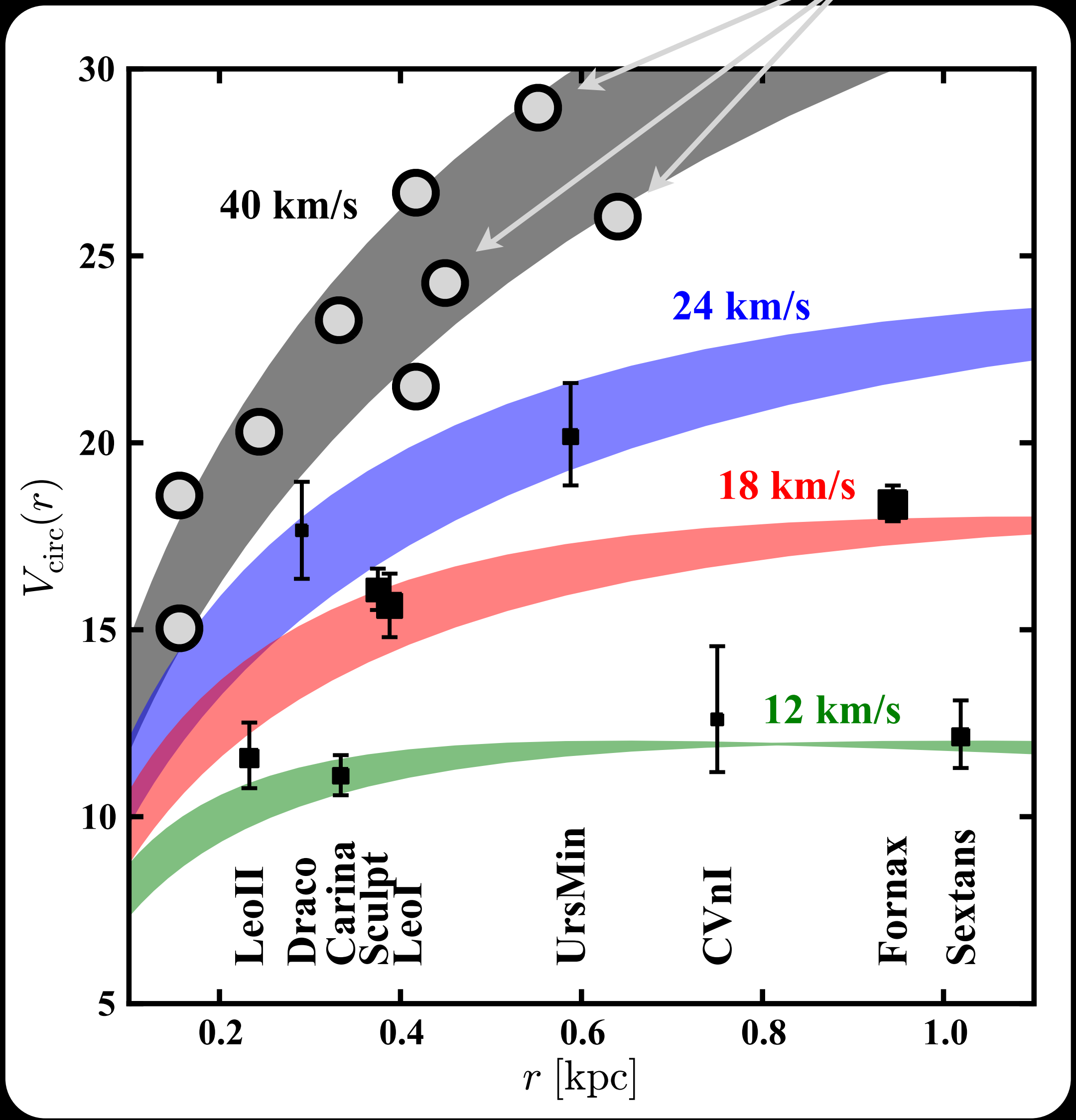


Boylan-Kulchin, Bullock, Kaplinghat, 2010 + 2011

Too Big to Fail

- The largest satellites are missing, based on comparisons of simulations of the satellites of typical Milky Way-sized galaxies..
- This is surprising: the largest galaxies are the most likely to contain baryons, and thus should be the easier ones for us to detect.
- The missing large galaxies were ``too big to fail"…

Where are these systems?!



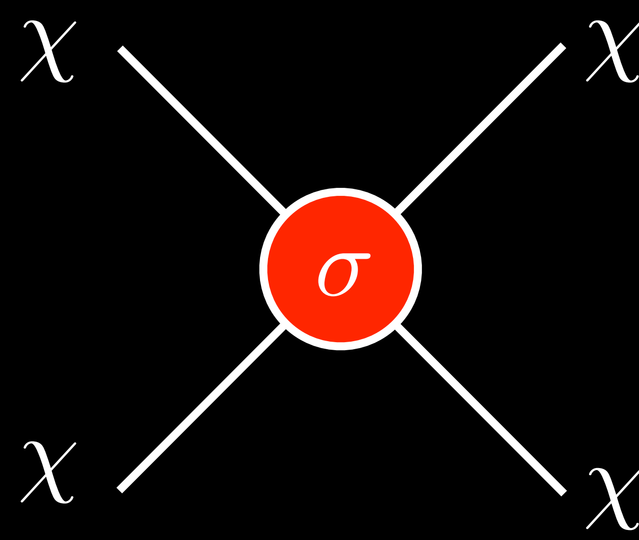
Boylan-Kulchin, Bullock, Kaplinghat, 2010 + 2011

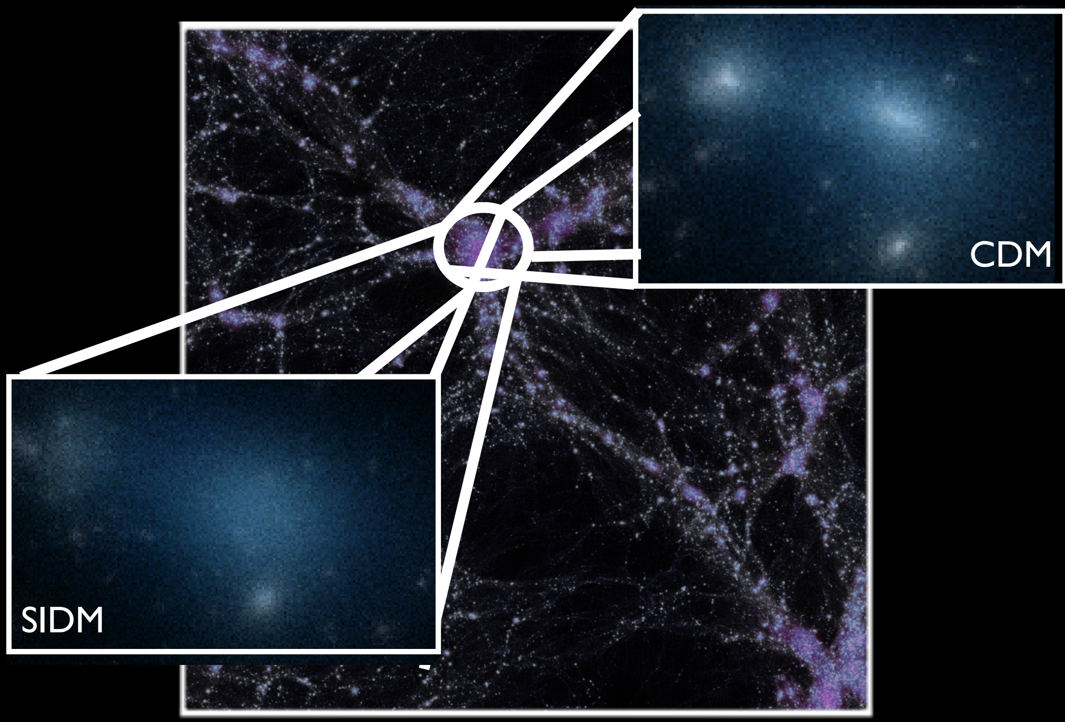
Caveats

- It is very interesting that all of these data seem to point to problems with CDM describing small scale structure. But given the success of CDM and reliance on simulations, we should be careful to leap to this conclusion.
  - The simulations used in the comparisons do not include baryons, which could impact the distribution of dark matter in the central regions through feedback.
  - Maybe the Milky Way is just a somewhat odd galaxy, with somewhat unusual satellites.
  - Maybe the Milky Way is actually a bit lighter than we think it is, and thus is expected to have less of the most massive sub-halos.
  - Maybe the process of being captured by the Milky Way disrupts the dark matter cores of its satellites.
- My attitude: this is an interesting (but complicated) set of data; it opens the door to theoretical exploration outside of the vanilla WIMP scenarios which can hopefully suggest other types of observational probes.

Self-Interacting Dark Matter

- One interesting class of solution invokes self-interaction of the dark matter.
- Self-interactions will allow dark matter in the densest regions to scatter, exchanging energy and smoothing out these extremely over-dense regions.
- Large scale structure will remain more or less the same.
- It also helps with the distribution of sub-halos around the most massive galaxies.
- The degree of self-interaction can be parameterized by σ / m.

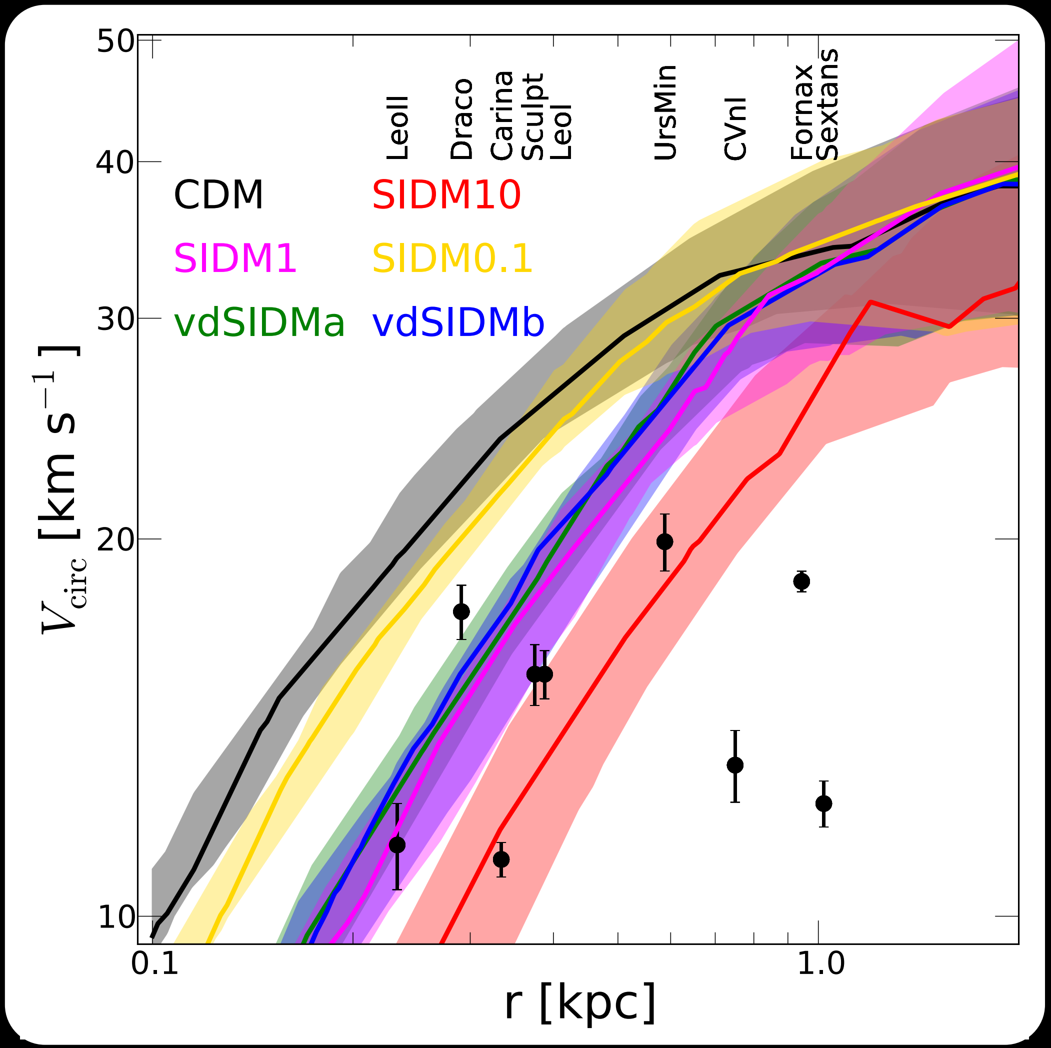




SIDM: Subhalos

- The number of sub-halos for a Milky Way-like galaxy can be extracted from simulations including the self-interactions.
- Simulations include both cross sections assumed to be roughly velocity-independent or velocity-dependent.
- Choosing σ / m ~ 0.1 to 10 cm^2 / g results in distributions that look a lot more like the population of observed dwarf galaxies.
- So self-interactions *can* help explain the observed distribution of the dwarf galaxies for the right cross sections.

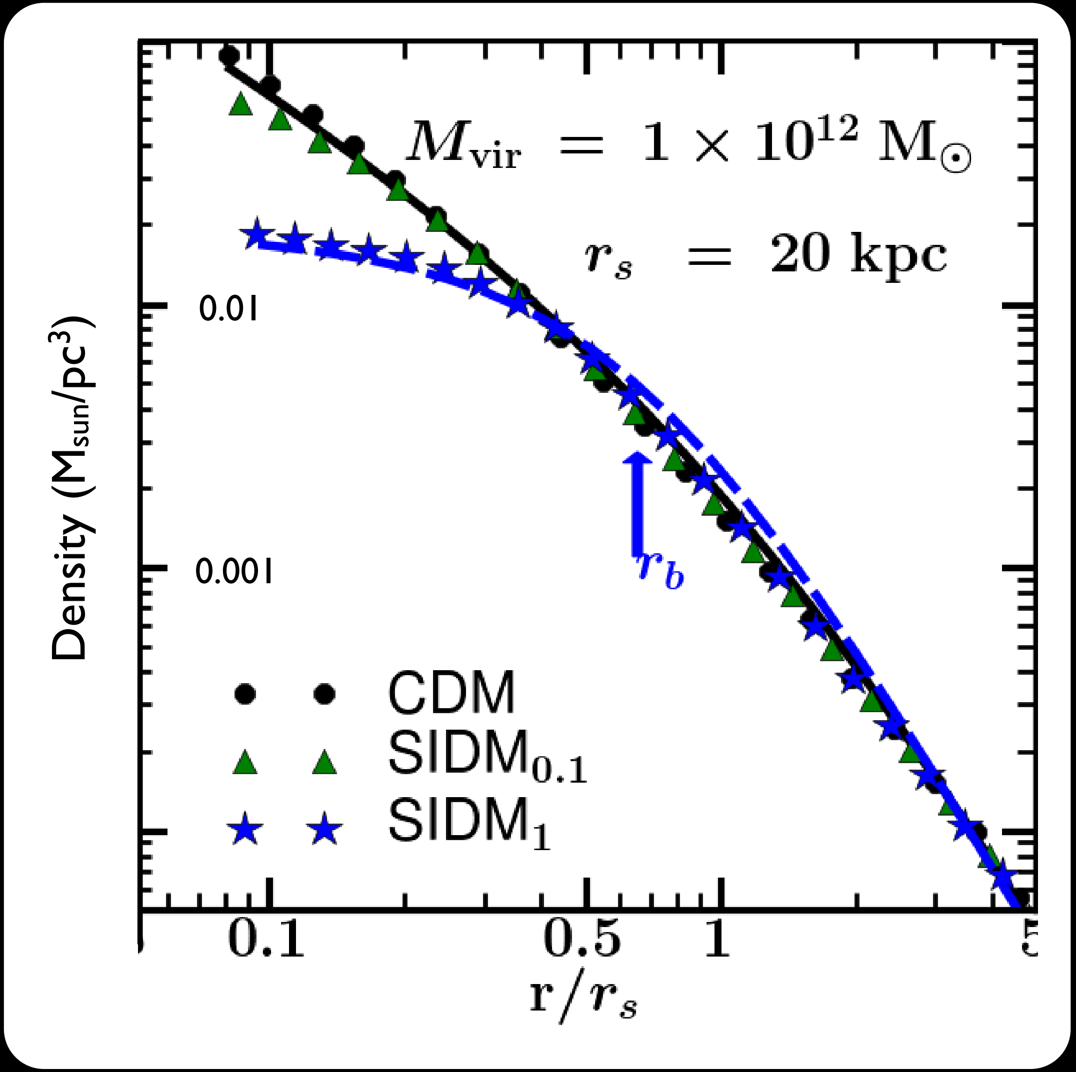
Vogelsberger, Zavala, Loeb 2012
Vogelsberger, Zavala, Walker 2012



Each colored band shows the heaviest satellite galaxies predicted by that simulation.

Cores

- As expected, self-interactions can also smooth out the cusps of dark matter halos.
- Interesting results occur for the same order cross sections as before: σ / m ~ 0.1 to 10 cm^2 / g.
- These can help explain the dwarf and spiral measurements.

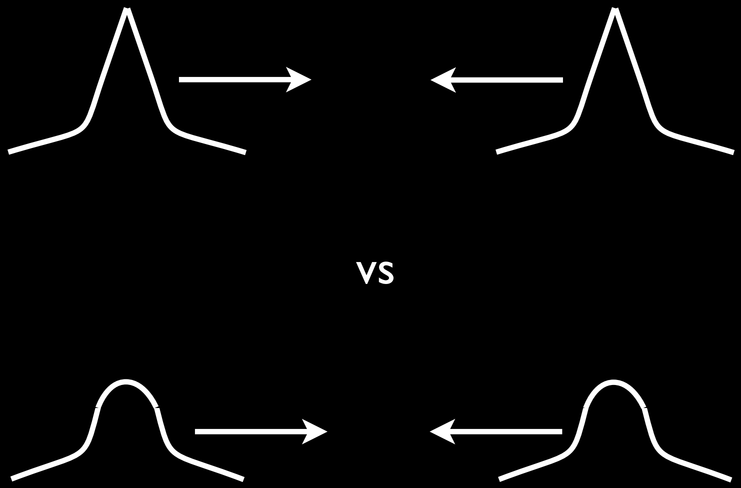


Rocha, Peter, Bullock, Kaplinghat, Garrison-Kimmel, Onorbe, Moustakas 2012

Constraints?

- There are constraints on the self-interaction cross section from observations of cluster mergers like the famous bullet cluster.
- Naively, the bullet cluster indicates σ / m < 0.7 cm^2 / g at a relative speed of ~3000 km/s.
- At face value, this constrains but does not exclude the lower range of interesting self-interaction cross sections with observable effects implied for dwarf galaxies.
- However, there is likely to be even more leeway, since this bound assumes ordinary NFW galaxies collide, whereas self-interactions will puff out the most dense regions, resulting in fewer scatterings.

Markevitch et al; Clowe et al



Model Building

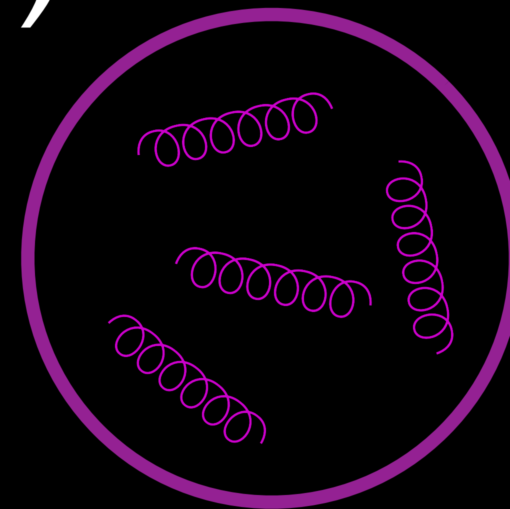
The Challenge

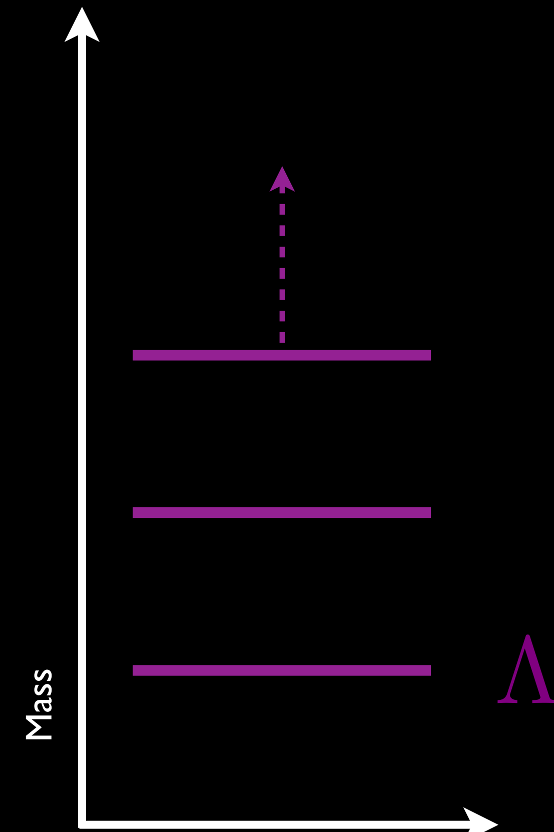
$$\frac{\mathrm{cm}^2}{\mathrm{g}} \quad \sim \quad \frac{1}{\mathrm{GeV}^3}$$

This is a large cross section for a vanilla weakly interacting massive particle, more typical of hadronic interactions.

A Dark SU(N)

- The simplest module we can consider is a pure gauge theory consisting of a hidden sector SU(N).
- To begin with, we imagine that any matter charged under the hidden gauge group and the SM is extremely heavy, and thus irrelevant for the low energy physics.
- At high energies, the theory is described by (somewhat) weakly coupled dark (hidden) gluons.
- The theory is defined by the number of colors N and confinement scale Λ, which characterizes the mass of the lowest glueball state, and the splitting between the various glueballs.
- From here on, dark/hidden should be understood whenever I use terms like "gluons" or "glueballs".





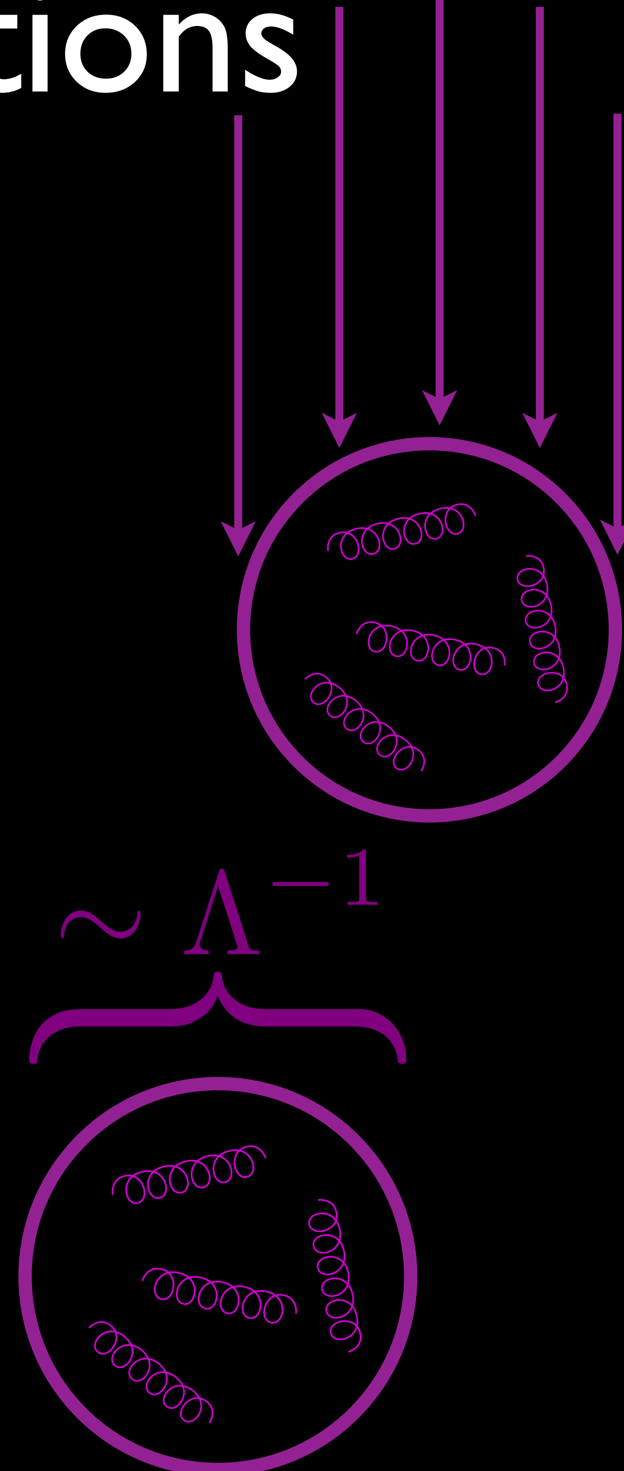
Glueball Interactions

- In this theory, nothing can be computed very reliably in perturbation theory.
  - Lattice is the way to quantitative understanding!
- We can cartoon the self-interactions of the glueballs by a geometric cross section of strongly coupled objects of size ~ 1 / Λ.

$$\sigma\left(\mathrm{gb\ gb} \rightarrow \mathrm{gb\ gb}\right) \sim \frac{4\pi}{\Lambda^2}$$

- Since the single parameter Λ controls both the mass and the cross section, arranging for an interesting value of σ/m essentially fixes Λ ~ 500 MeV.

Amusingly close to Λ_{QCD}…



Glueball Relic Density

- We can estimate the relic density of the glueballs by tracking the relic density of the gluons to the temperature at which the theory confines.
- At this temperature, something around Λ, the energy in the dark gluons will get converted into glueballs.
- We can estimate the relic density of glueballs by matching across the phase transition.
- If there are no relevant connectors between the visible and hidden sectors, the temperature in the hidden sector T^h and the visible temperature T could generically be different.
- We parameterize this possibility with the ratio of temperatures $\xi = T^h / T$.
- There are interesting corrections to the usual thermal distribution: cannibalization!

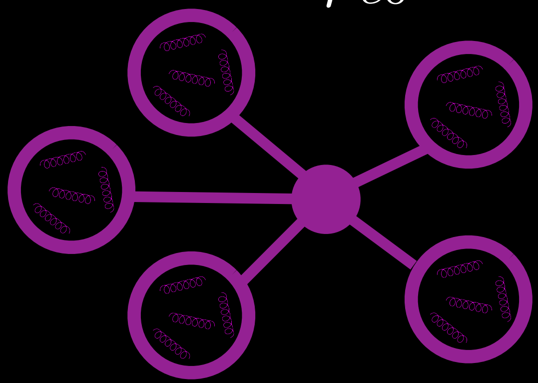
$$Y \equiv \frac{n_{\rm gb}}{s}$$

$$= \frac{g_{\rm eff}[\zeta(3)/\pi^2]T_h^3}{g_{*S}[2\pi^2/45]T^3}$$

$$= \frac{g_{\rm eff}45\zeta(3)}{g_{*S}2\pi^4} \times \xi_f^3$$

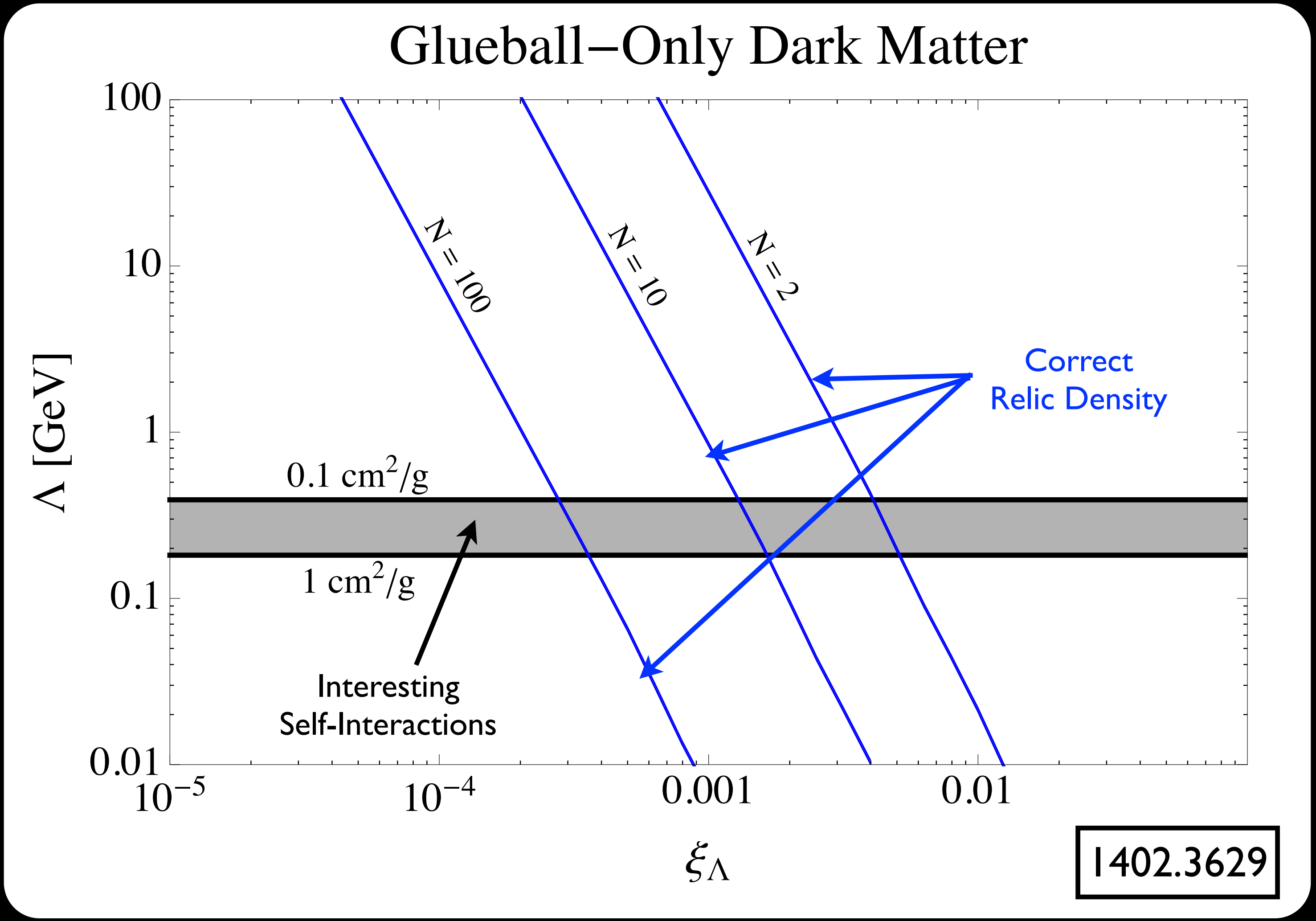
For SU(N), $g_{\rm eff} = 2 \times (N^2-1)$

$$\Omega_{\rm gb} \sim \frac{Y s_0 \Lambda}{\rho_{c0}}$$



Carlson, Machacek, Hall 1991
Hochberg, Kuflik, Volansky, Wacker 2014

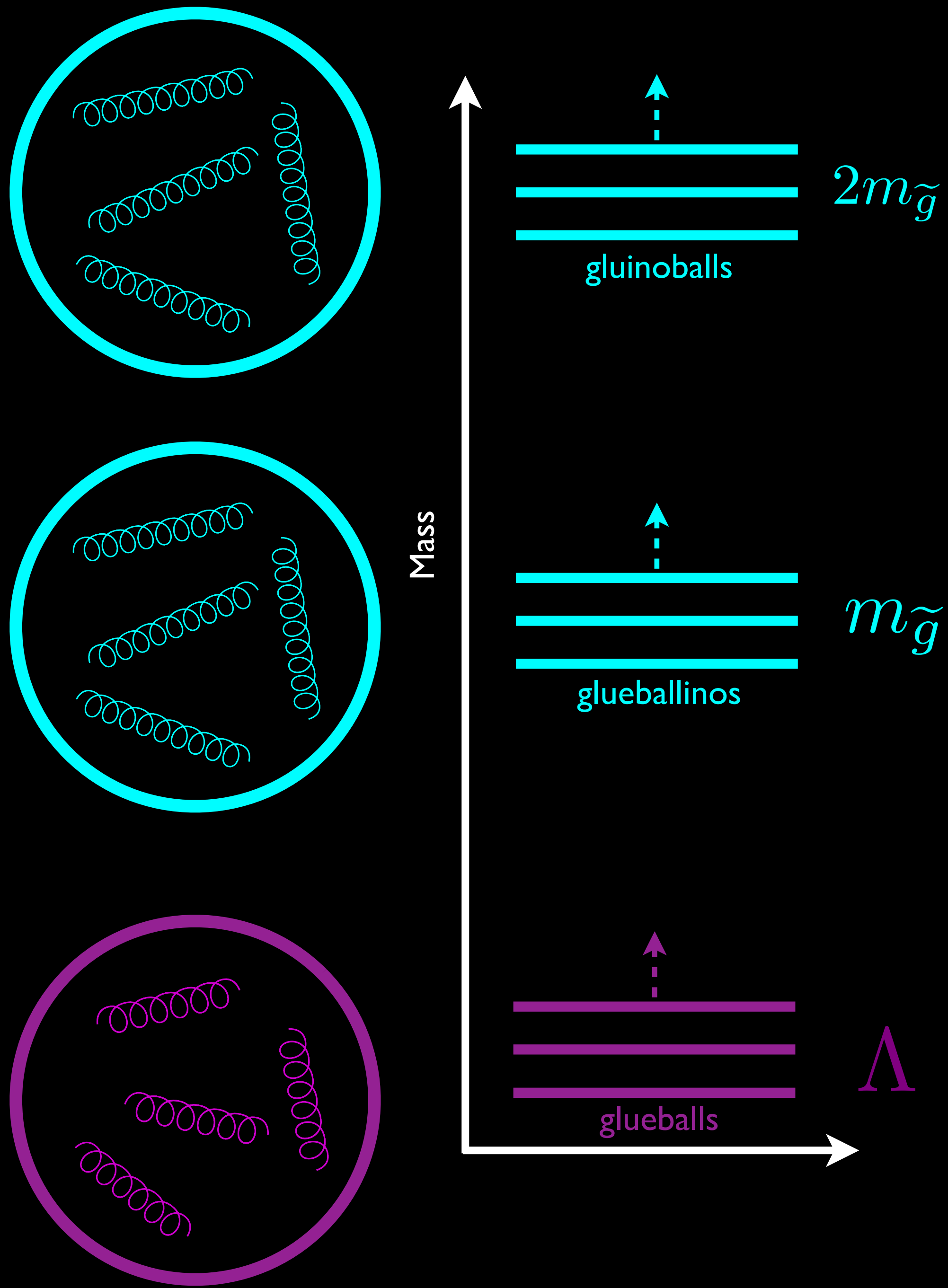
Glueball Parameter Space



- For a given N, there are two parameters, the confinement scale and the ratio of hidden to visible temperatures at the time of confinement, ξ_Λ. Provided one allows for a somewhat colder hidden sector, one can achieve interesting self-interaction rates at the observed relic density!

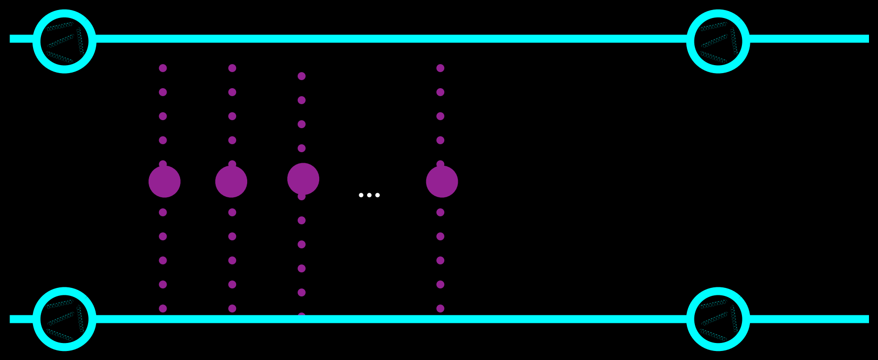
SU(N) + Adjoint

- A very simple extension is to add an adjoint (Majorana) fermion to the dark sector.
- If one likes, this could be considered a supersymmetrized version of the pure gauge model, with the adjoint playing the role of the gluino.
- The spectrum consists of glueballs as before, and (for m >> Λ) a family of fermionic glueballinos at mass ~ m.
- These glueballinos are strongly interacting with the glueballs and are sort of analogues of heavy-light mesons in this theory.

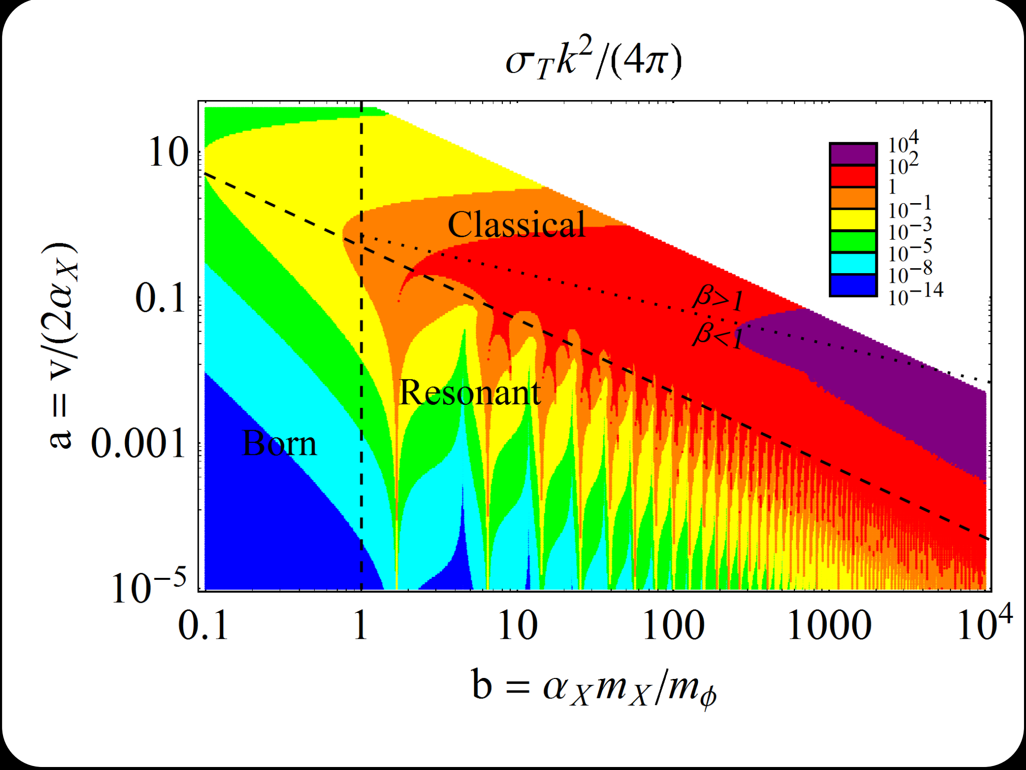


Self Interactions

- The glueballinos are strongly interacting with the glueballs, which mediate scattering.
- When m >> Λ, one generally expects large cross sections with the possibility of Sommerfeld-like enhancements.
- We model the glueball exchange as a Yukawa potential characterized by mass ~Λ and strong coupling.
- We (numerically) solve for the transfer cross section as a function of the masses of the glueballs and glueballinos, and average it over the velocity distribution of the dark matter for each system.



$$\sigma_T \equiv \int d\Omega (1 - \cos\theta) \frac{d\sigma}{d\Omega}$$

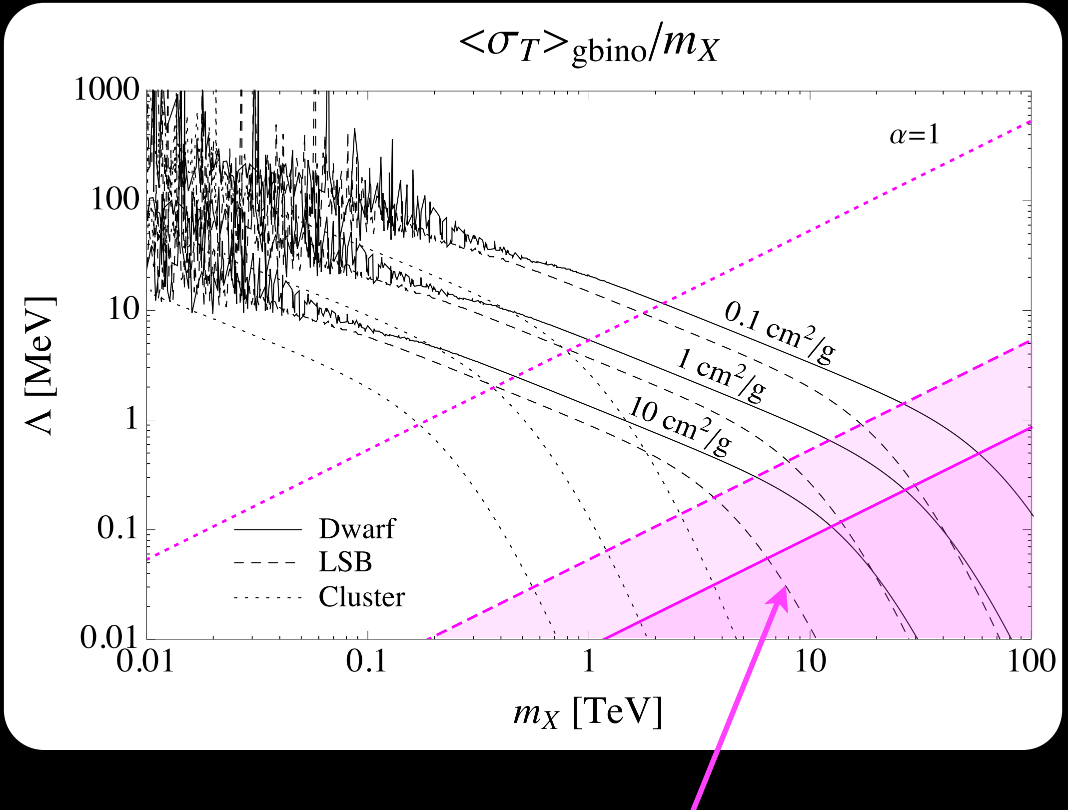


Tulin et al 2013

Glueballino Scattering

- We can obtain scattering cross sections in the ballpark of the interesting region for gluino masses on the order of TeV and Λ ~ MeV.
- Since each type of astrophysical object is characterized by a different DM velocity, the cross sections are different for each one.
- If the typical kinetic energy is large enough, inelastic channels will open up, and our transfer cross section may not characterize the scattering very well.
- Clusters are very likely to have inelastic processes playing some role.

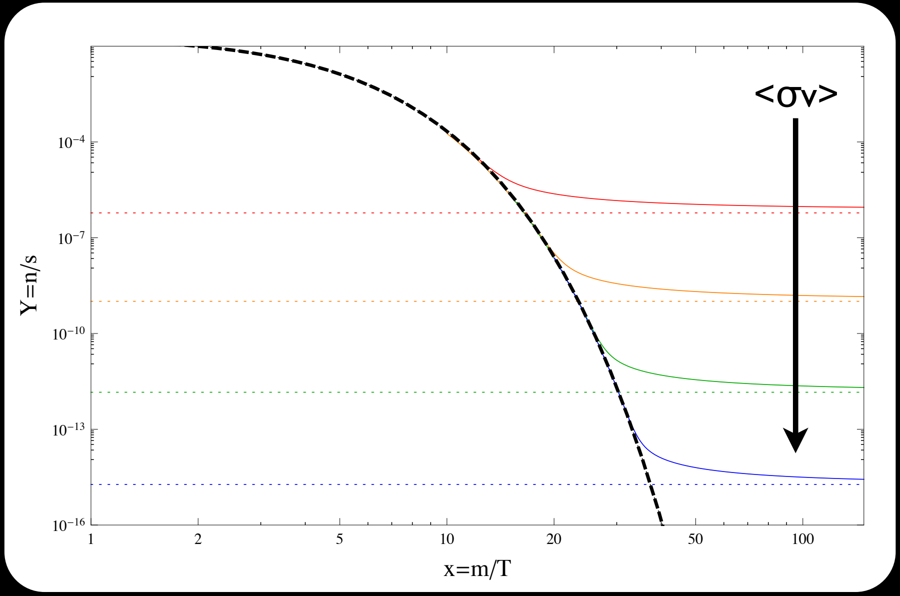
Object	Typical v
Clusters	700-1000 km/s
LSB	50-130 km/s
Dwarf	20-50 km/s

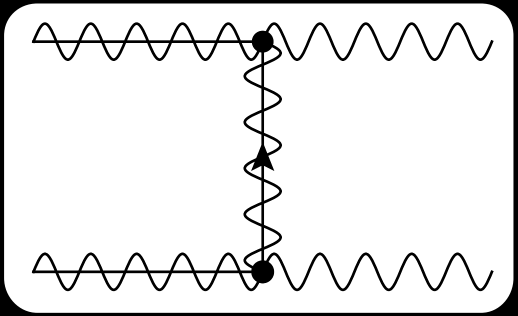


$$E_{\rm kin} = \frac{1}{2}mv^2 \gtrsim \Lambda$$

WIMPless Miracle

- In the regime m >> Λ, the dark gluinos will freeze out when their gauge couplings are still perturbative, and this stage looks like a rather standard WIMP.
- Without connectors to the SM, they only couple to the dark gluons, and once again there is generally a separate temperature that characterizes the hidden sector.
- The context of a SUSY breaking model such as AMSB, this allows us to inherit the nice feature of the `WIMPless' miracle.
- We know that weak couplings and masses produce the correct relic density, and AMSB fixes the ratio such that it works out for the hidden sector too.





$$\langle \sigma v \rangle \propto \frac{\alpha^2}{m^2}$$

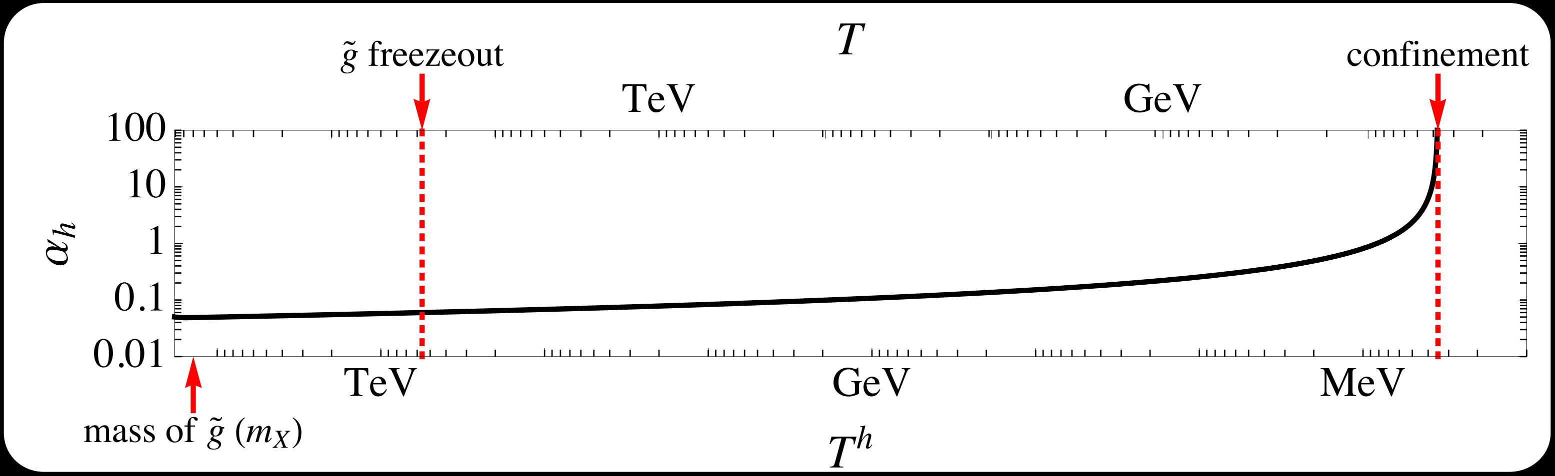
Feng, Kumar 2008

$$m \sim \frac{\alpha}{4\pi}\beta \times m_{3/2}$$

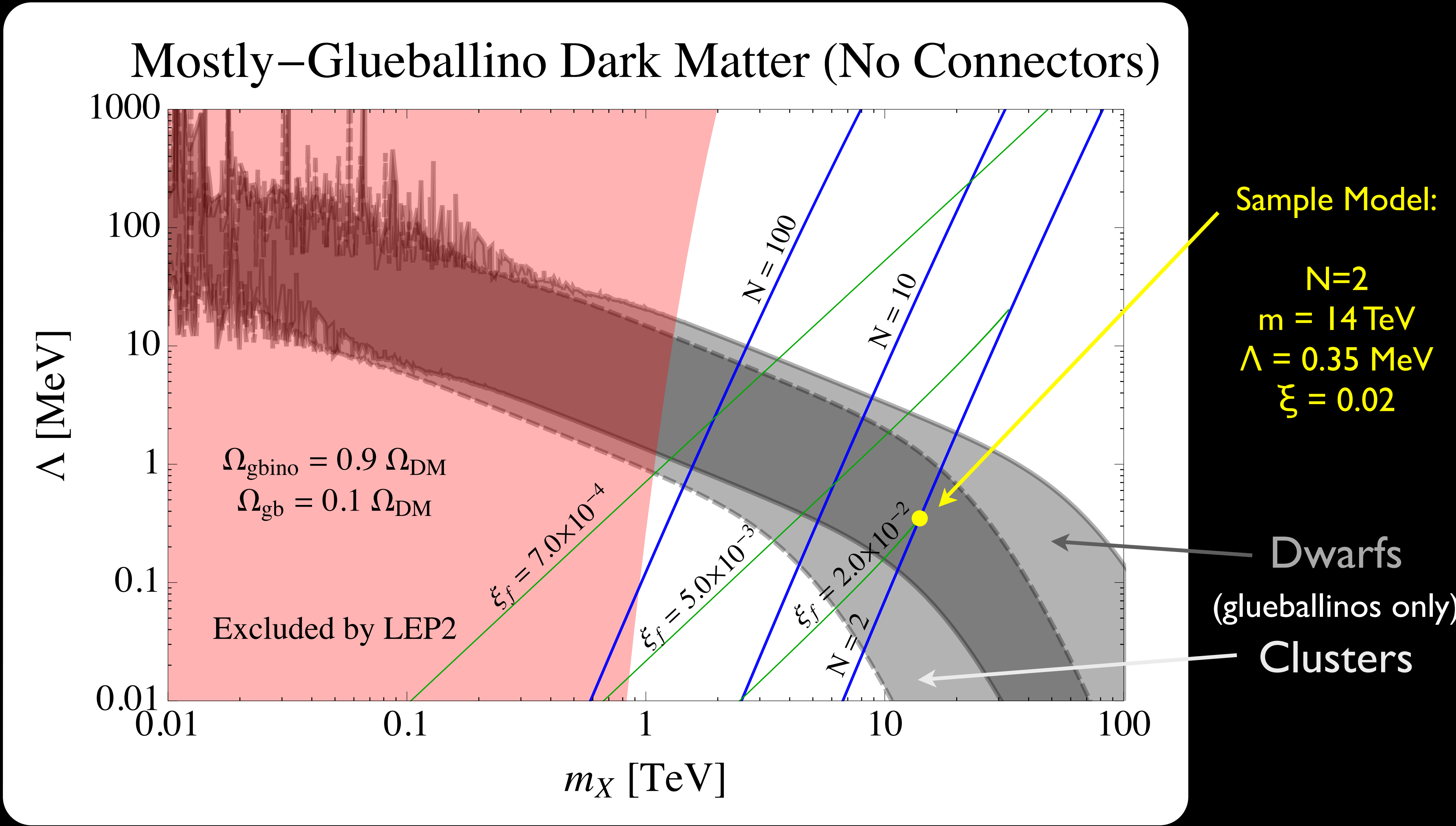
$$\frac{\alpha^2}{m^2} \sim \frac{\alpha_W^2}{M_W^2}$$

Mixed Dark Matter

- Since the theory will still contain glueballs, this is generically a theory of multi-component dark matter.
- Which component will dominate depends on their relative masses (m and Λ) and the temperature in the hidden sector, ξ.
- The precise behavior under structure formation for this kind of multi-component system probably requires simulations to understand properly. We'll look at some representative limiting cases.



Glueballino Dominated

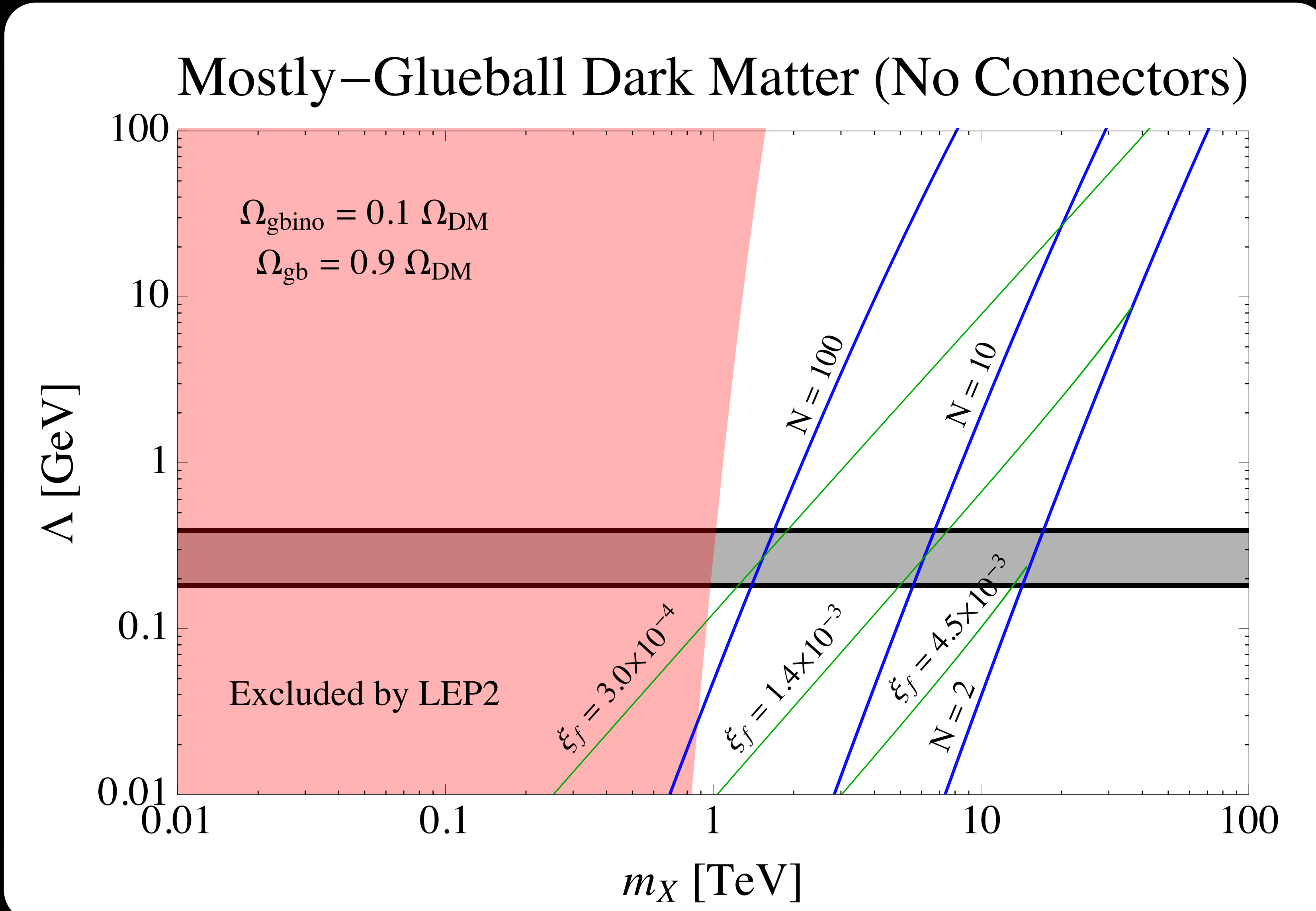


Pink shaded: LEP-2 wino bound

Blue curves: N fixed (ξ varies)

Green curves: ξ fixed (N varies)

Glueball Dominated



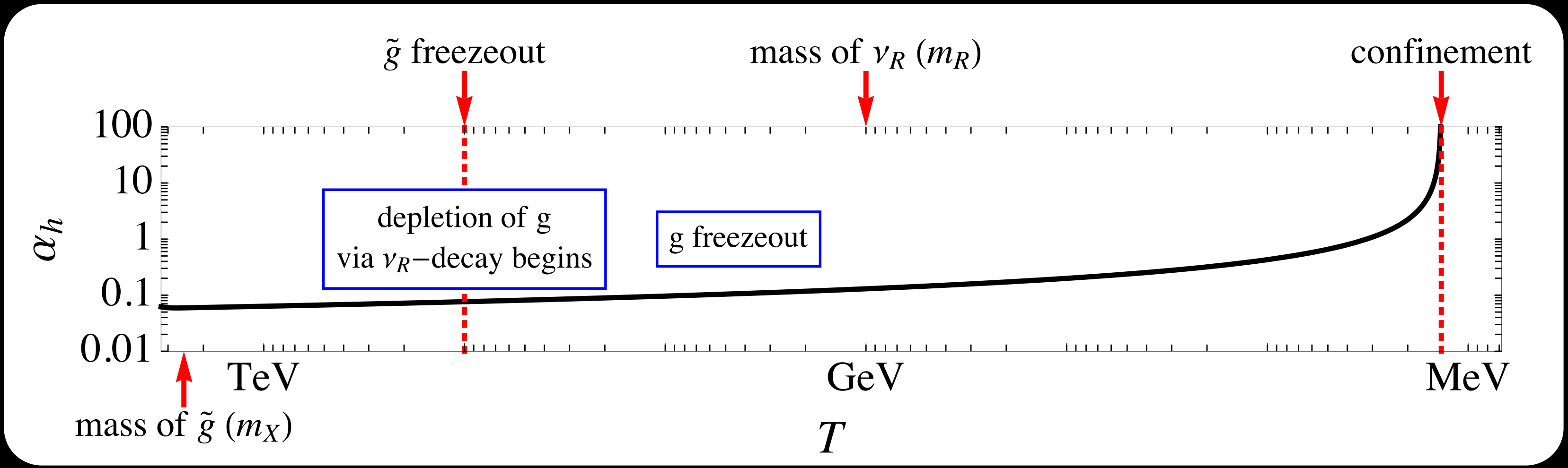
(glueballs only)

Pink shaded: LEP-2 wino bound

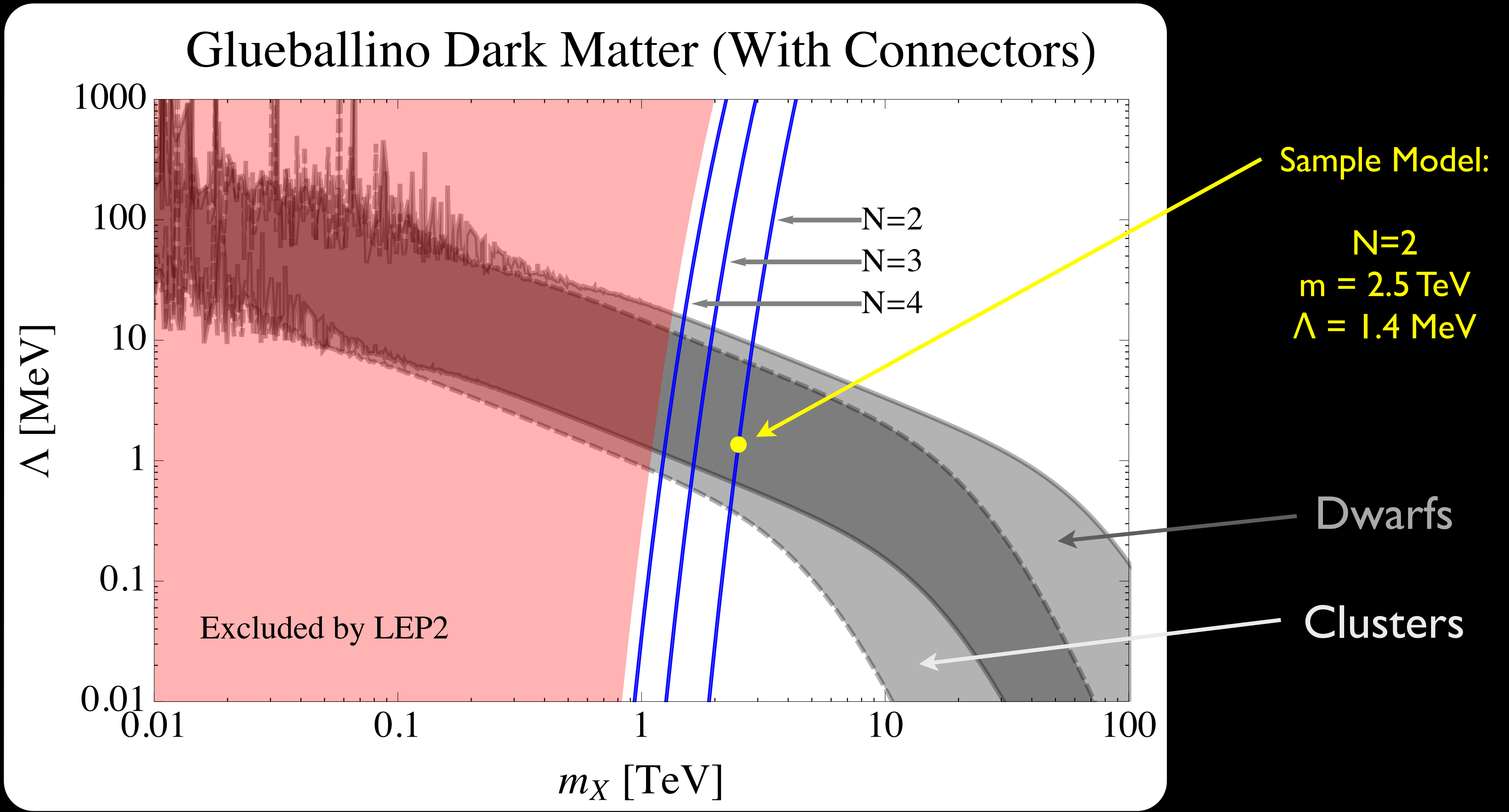
Blue curves: N fixed (ξ varies)
Green curves: ξ fixed (N varies)

Connection to the SM

- If we introduce matter charged under both the SM and the hidden gauge symmetry, the dark matter begins to look more like a standard WIMP.
- The temperatures in the visible and hidden sectors will equalize, and in general the dark glueballs will be able to decay.
- In general, this last fact is a problem, because for Λ ~ MeV, the dark glueballs will typically be over-produced, and decay too late, interfering with BBN.
- We cartoon a mechanism to remove the glueball density after the gluinos freeze out, by having them annihilate efficiently to sterile neutrinos, which themselves decay quickly into ordinary neutrinos.



Connected to the SM



Pink shaded: LEP-2 wino bound

Blue curves: N fixed

Future Directions

- There are a lot of interesting directions one could follow from here.
  - A generic feature is the presence of multiple components of dark matter with very different masses and scattering cross sections. One can easily imagine very different profiles for the two components (as in e.g. "double disk dark matter"). Fan, Katz, Randall, Reece 2013
  - If the subdominant component is strongly self-interacting, it could collapse and accrete on supermassive black holes. There is actually a mystery as to where $10^9 \times M_{sun}$ black holes come from, and this kind of scenario could help understand it. Hennawi, Ostriker 2001 Pollack et al 2015
  - On the other hand, if too much dark matter accretes into the black holes, it will conflict with the observed ratios of sizes of central black holes to their host halos.
  - Inelastic processes could be important, especially on cluster scales, and could lead to interesting effects such as halo evaporation/collapse.

A keV Line?

- Inelastic processes could lead also to interesting signals in the vein of eXciting dark matter.

Finkbeiner, Weiner 2007

- This might even be relevant for the few keV X-ray line that has been recently observed in a stacked analysis of galaxy clusters (and perhaps Andromeda).

Bulbul et al 2014
Boyarsky et al 2014

- The desired cross section for an eXciting explanation of the observation is in the same ball-park as the SIDM cross sections we have been discussing.

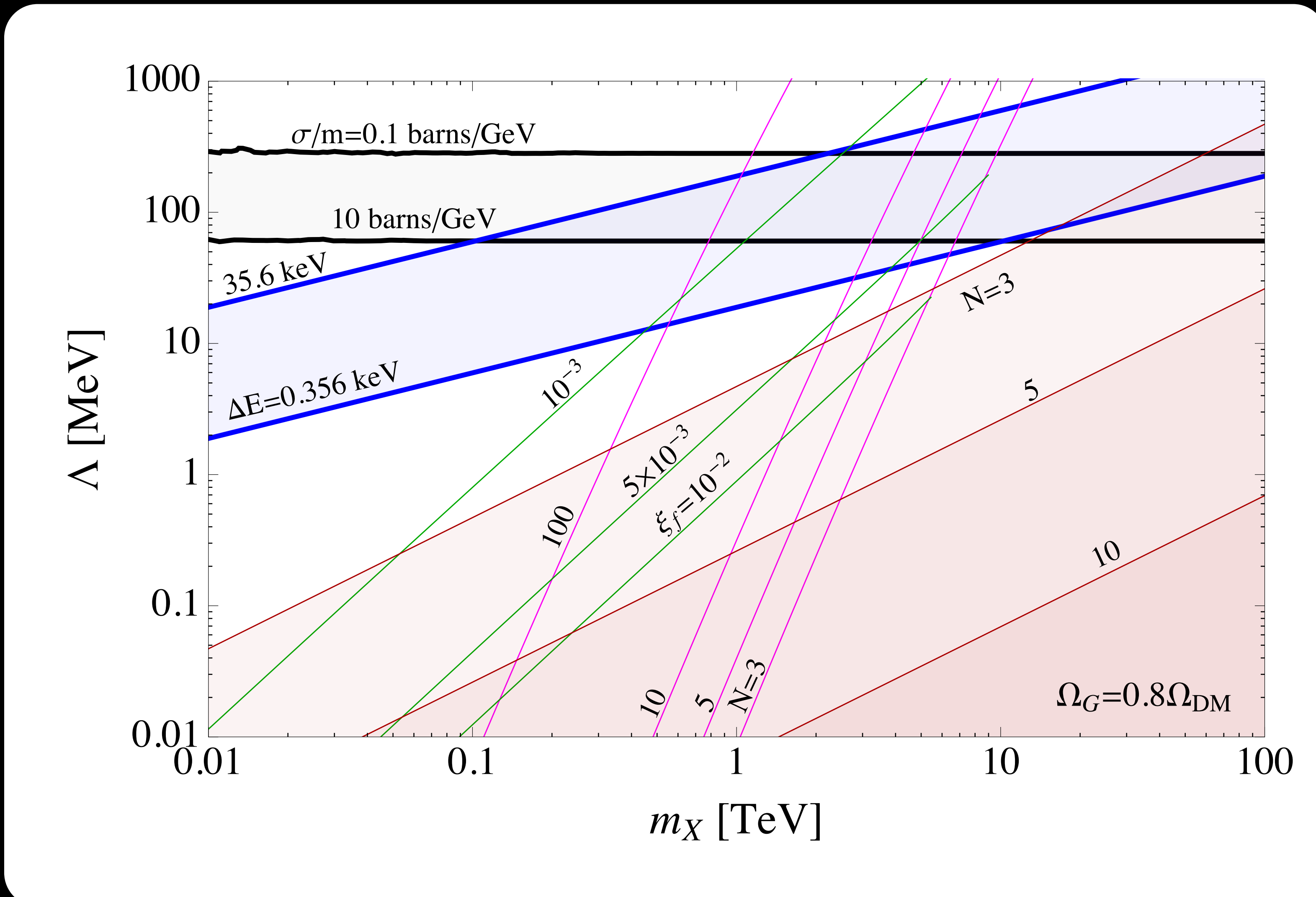
Finkbeiner, Weiner 2014

- The glueballino system contains states whose masses are split by the analogue of hyperfine interactions, and are ~ Λ^2 / m.

- For m ~ few hundred GeV and Λ ~ 10's MeV, we the right characteristic splitting to explain the energy of the line, and are still in the target cross section to explain the rate as well as have a theory with interesting SIDM.

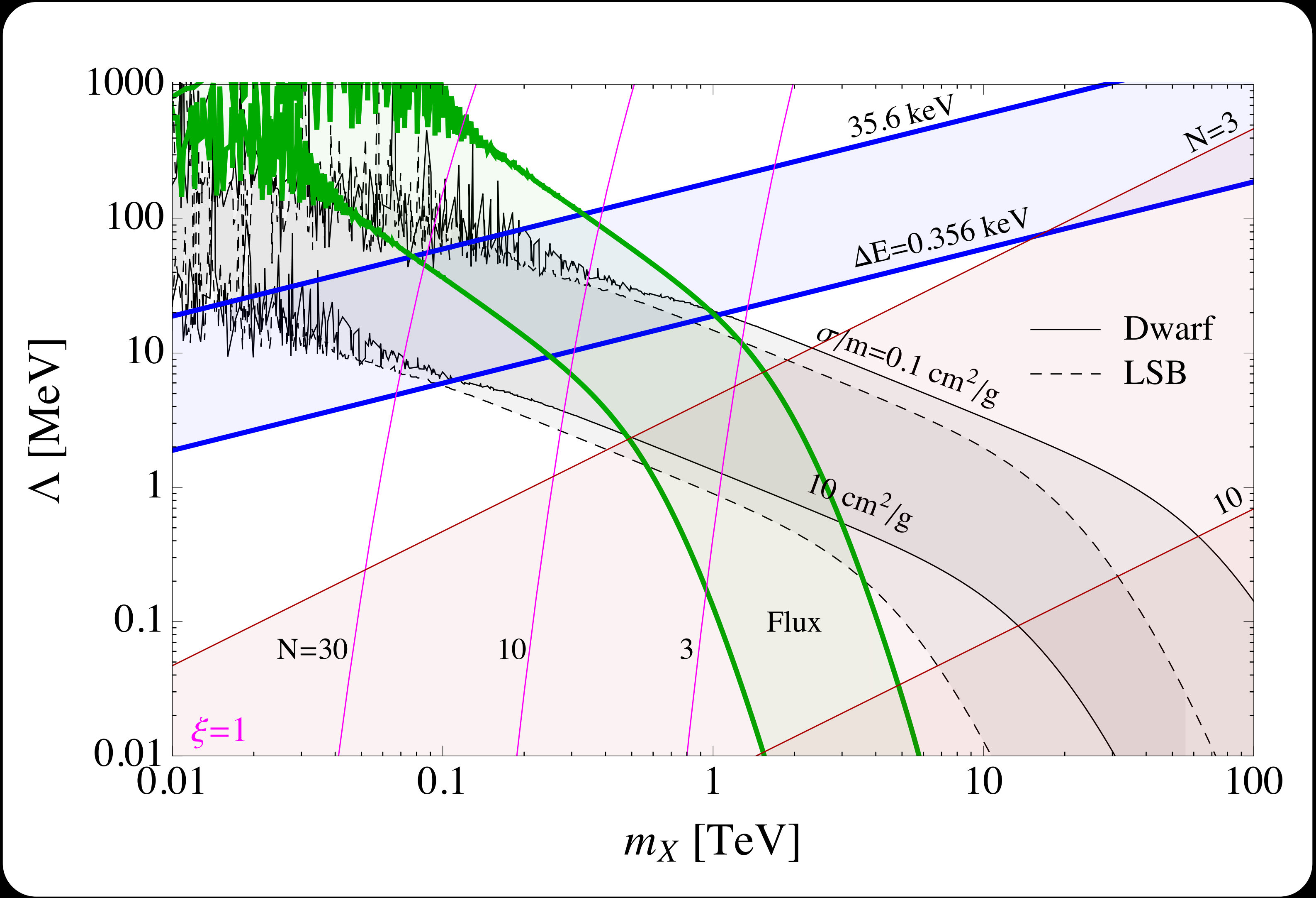
Boddy, Feng, Kaplinghat, Shadmi, TMPT 1408.6532

keV Line



One possibility is to have most of the dark matter in the form of glueballs, which are self-interacting. The subdominant glueballino component has a primordial population of excited states. If we tune the lifetime to τ ~ 30 Gyr, we can explain the intensity of the Bulbul et al line.

keV Line



If we deplete the glueballs as before, the dark matter is entirely glueballinos and we can either invoke a long lifetime scenario, $\tau \sim 10^3$ Gyr, or the excited states could be generated via up-scattering of the dark matter through its strong (self) interactions provided $\tau \sim 10^{15}$ s.

Conclusions

- There are interesting puzzles when one looks at the small scale structure of the Universe.
- While subject to the limitations of simulation and a lot of astrophysical uncertainty, the fact that a number seem to point in the same direction may indicate cracks in the CDM paradigm.
- Large self-scattering of the dark matter is one possible solution. I explored the idea that the dark matter could be a composite particle as a way to realize the large cross sections.
- These models naturally lead to multiple components of dark matter, some of which may be strongly self-interacting. There are a lot of astrophysical and simulation issues to understand if this is the case.
- More generally, the study of structure could provide a unique window on particle properties of dark matter which are very difficult to access through the standard particle physics searches.

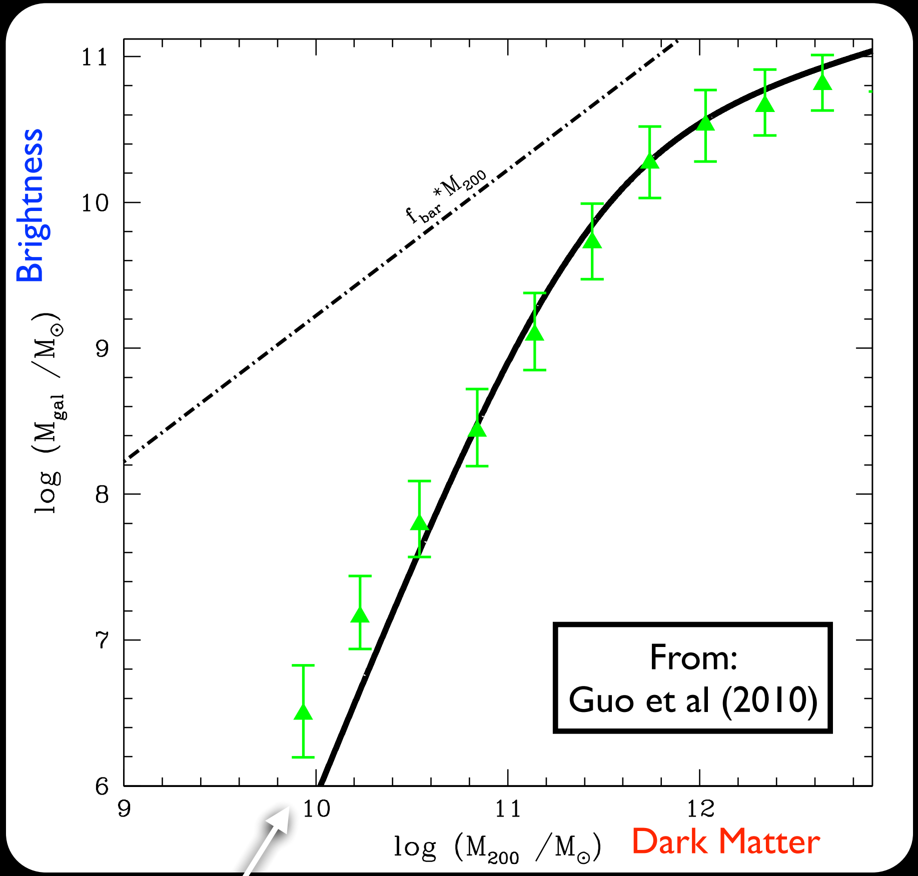
Bonus Material

Outline

- Motivation: Dark Matter with Self-Interactions?
  - Evidence from small scale structure
- A non-Abelian Framework
  - Dark Matter as dark glueballs
  - Dark glueballinos
- Outlook

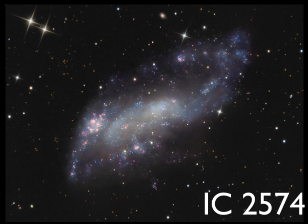
Dwarf Spiral Galaxies

- Another probe comes from small nearby spiral galaxies with masses around 10^{10} x M_{sun}.
- A first thing one can look at is population statistics: CDM simulations predict a distribution of masses for such galaxies.
- By comparing the distribution of galaxies observed to the distribution in the simulations, one can establish a mapping between the brightness of the galaxy (M_{gal})and the predicted mass of the halo from the simulation.
- Essentially no galaxies with $M_{gal} > 10^6$ x M_{sun} should form in dark halos lighter than 10^{10} x M_{sun}.



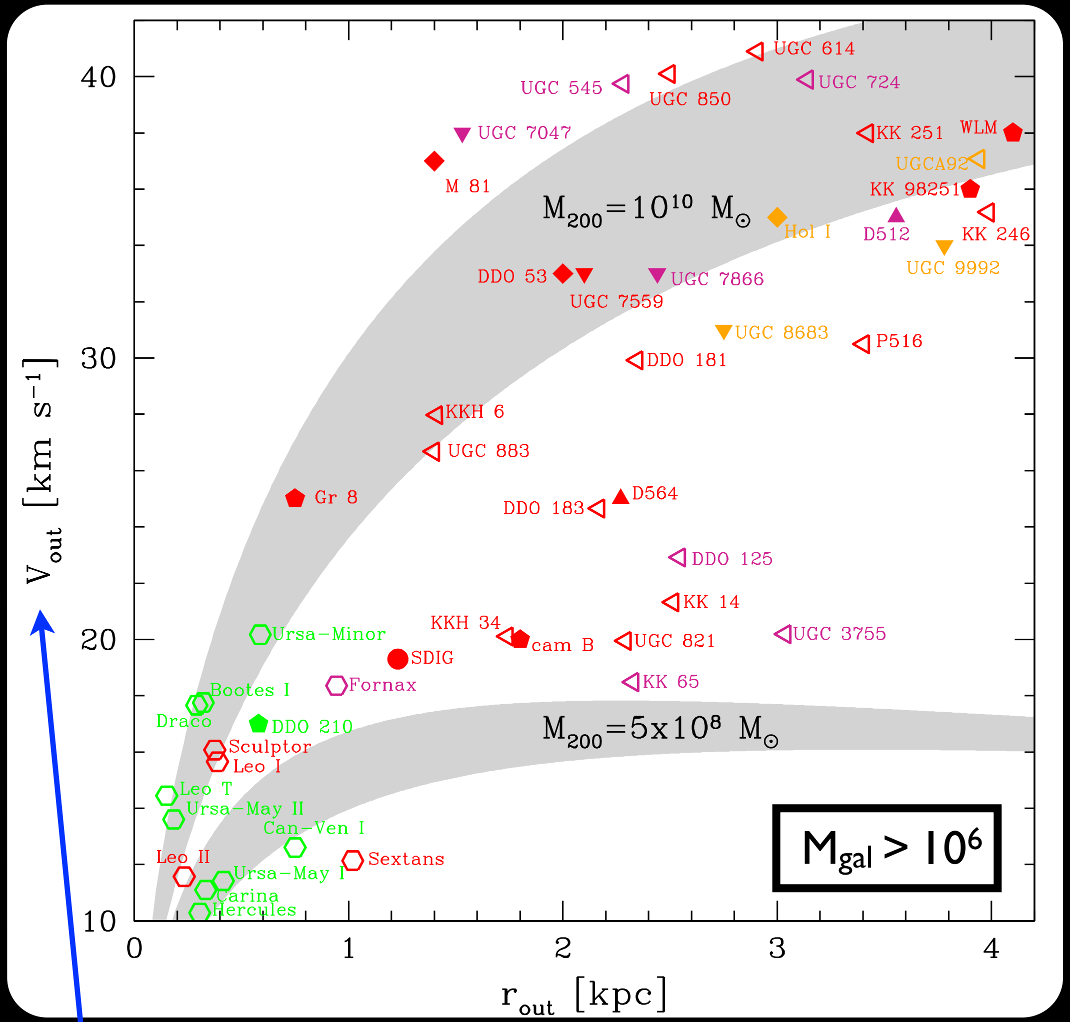
Ferrero et al (2012)

Steep fall-off for simulation masses below 10^{10}



Dwarf Spiral Galaxies

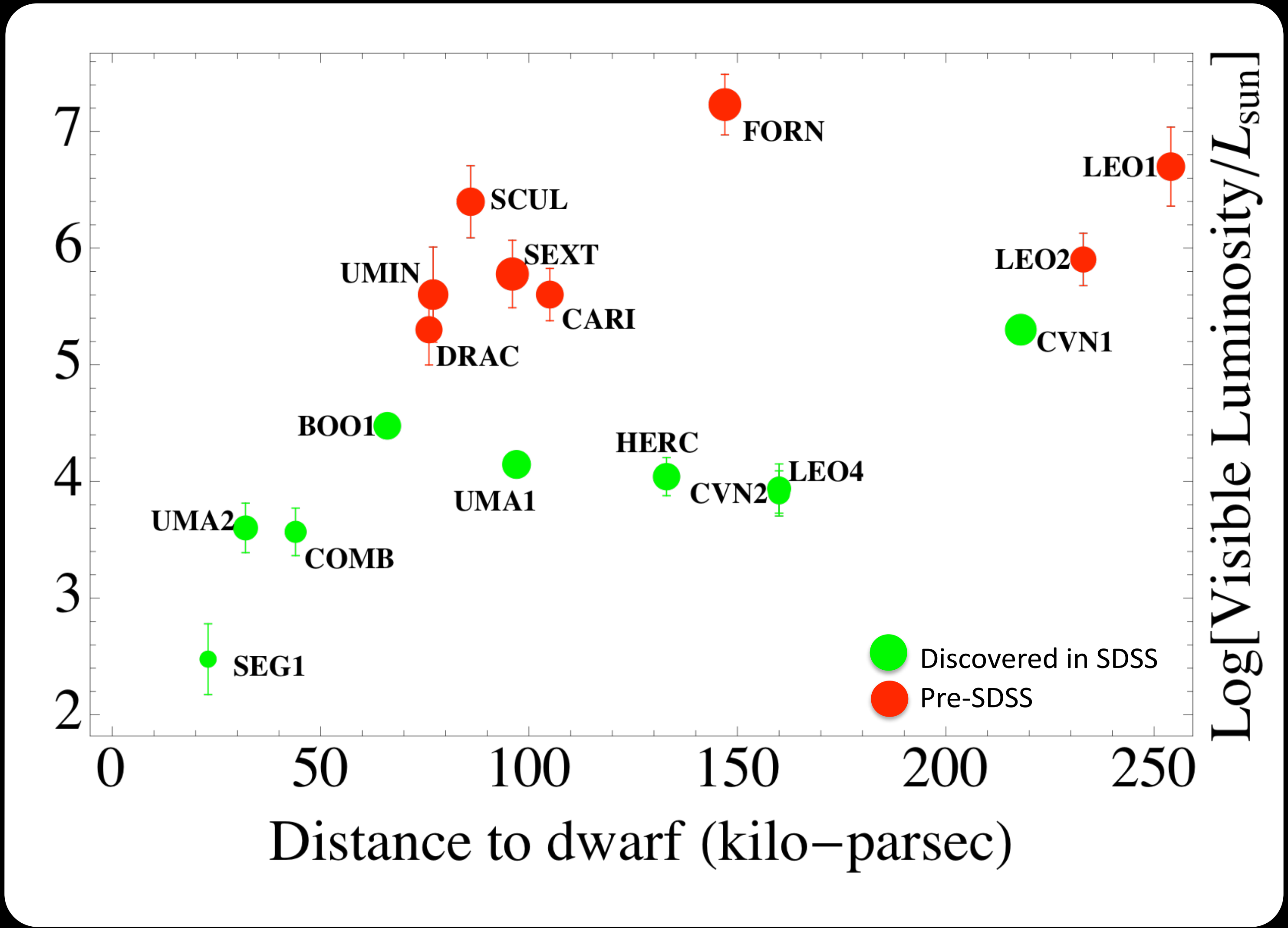
- Using measurements of the rotation curves of one of these galaxies gives an independent determination of its mass, which is characterized by the velocity of the outermost stars.
- Already at the level of population statistics, there seems to be something odd.
- Their brightness suggests that their masses should be above around $10^{10} \times M_{sun}$.
- But many of them have dynamics which are more consistent with masses much lower than that.



Ferrero et al (2012)

Correlates with total Mass

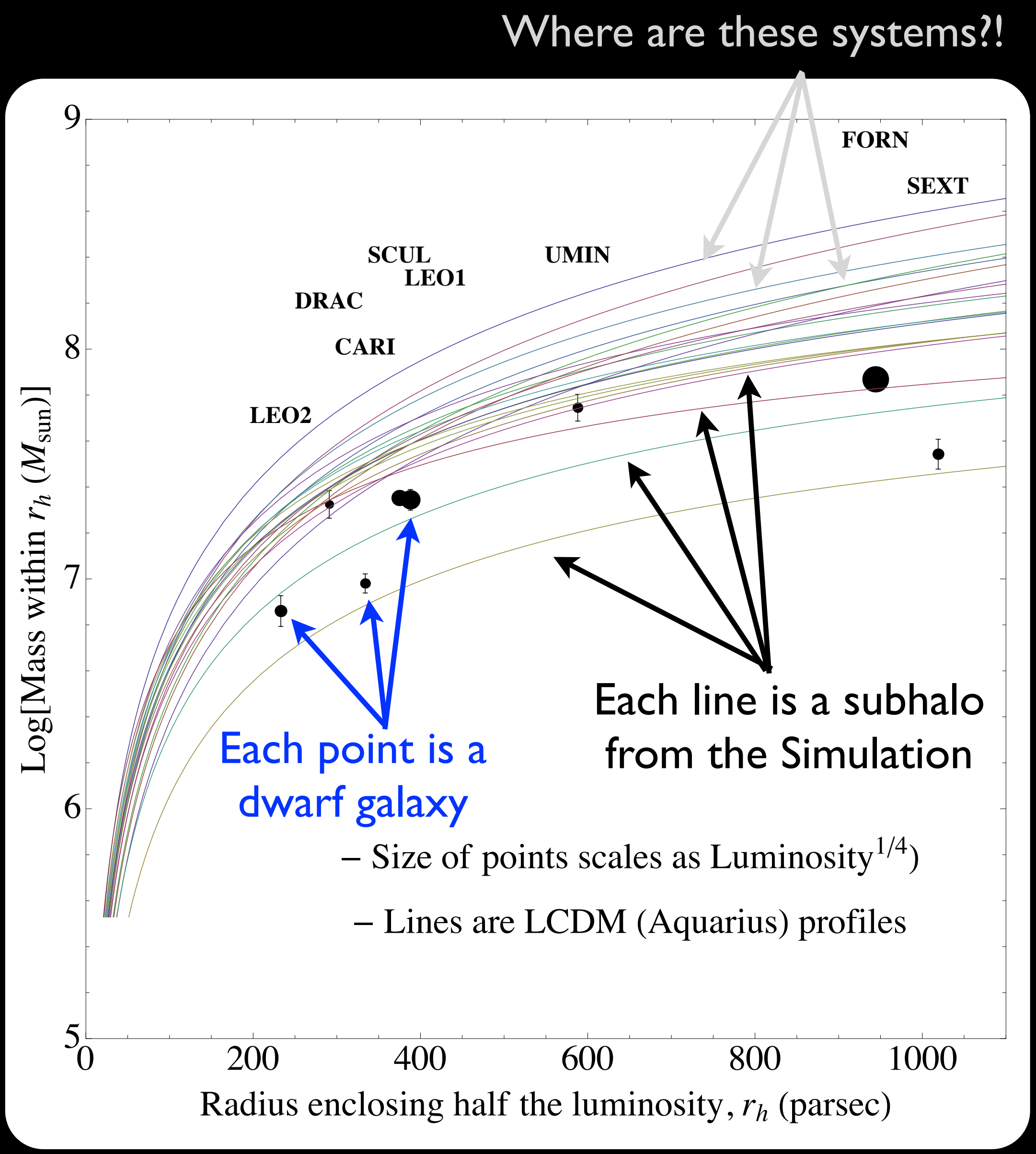
Dwarf Spheroidals



- We can also look at the spheroidal dwarf galaxies of the Milky Way.
- Based on their kinematics, these systems are highly dark matter-dominated.

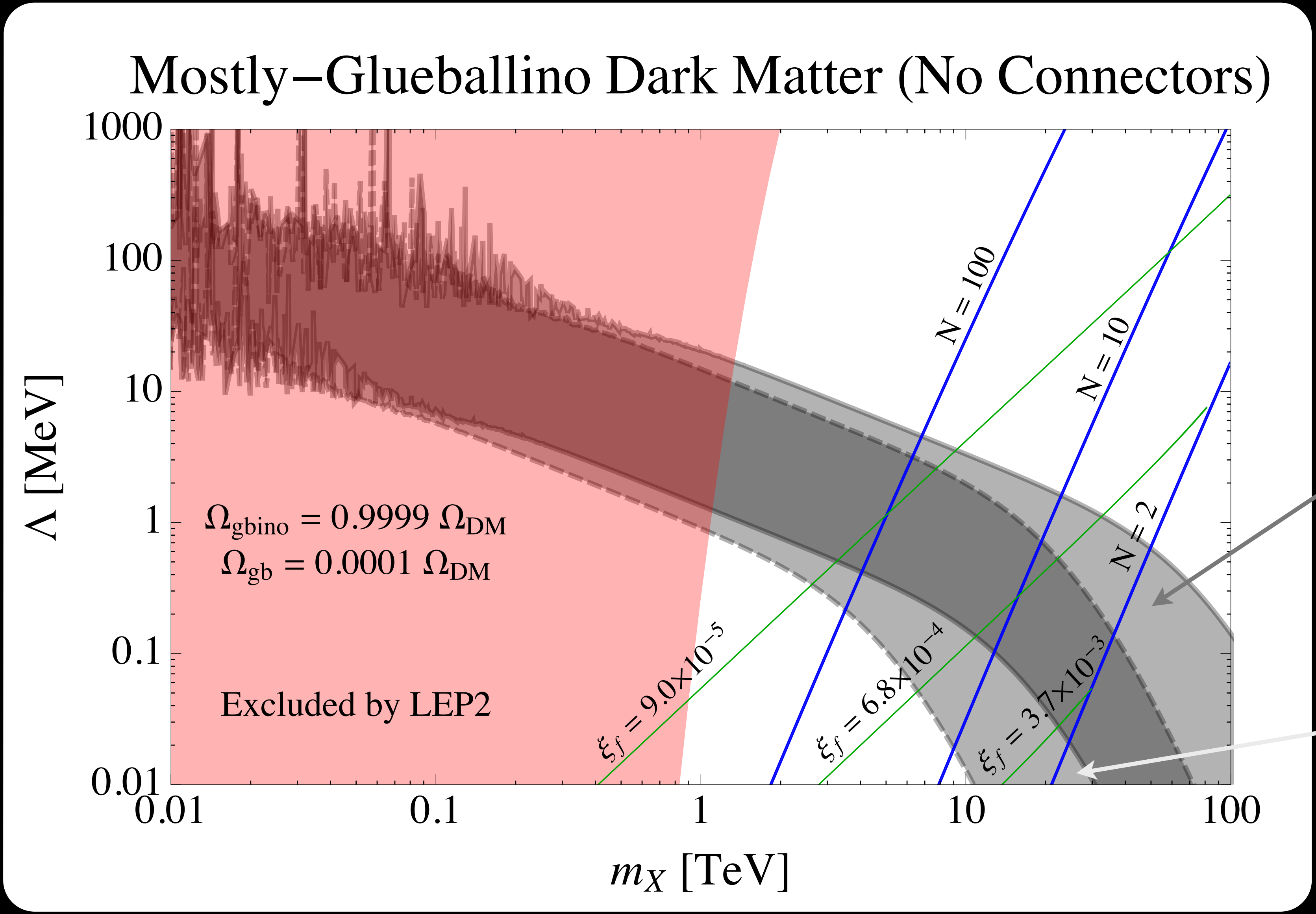
Too Big to Fail

- One possibility would be if for some reason the most massive halos don't light up.
- But that is hard to swallow: the more massive objects should end up containing more baryons than the less massive ones.
- It's hard to believe that galaxies this large would not contain stars that would allow us to "see" them.
- These missing large satellite galaxies are "too big to fail"...



Boylan-Kolchin, Bullock, Kaplinghat, 2010 + 2011

Glueballino Dominated

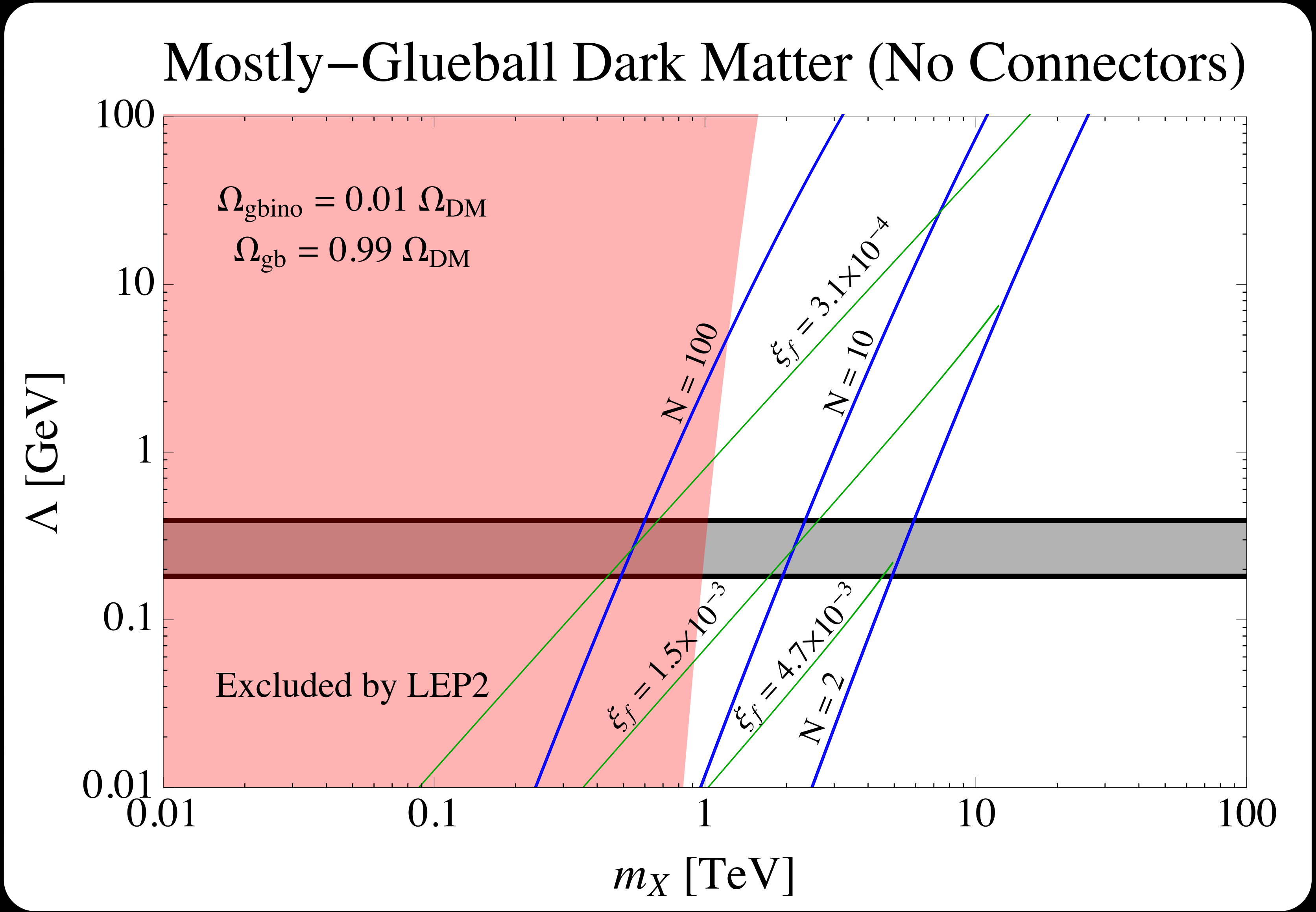


Pink shaded: LEP-2 wino bound

Blue curves: N fixed (ξ varies)

Green curves: ξ fixed (N varies)

Glueball Dominated



(glueballs only)

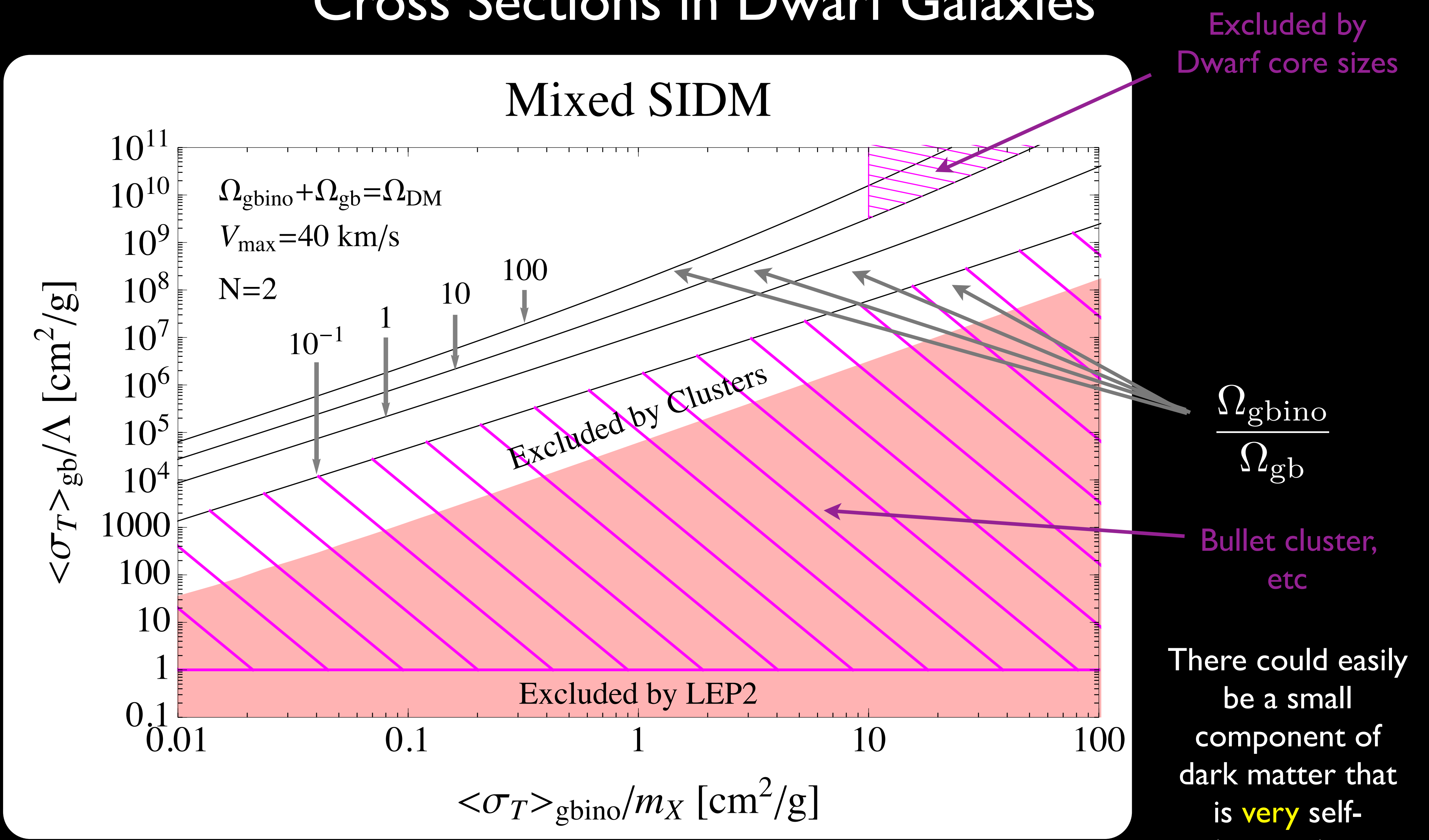
Pink shaded: LEP-2 wino bound

Blue curves: N fixed (ξ varies)

Green curves: ξ fixed (N varies)

Mixed SIDM

Cross Sections in Dwarf Galaxies



There could easily be a small component of dark matter that is very self-interacting.